usually be needed to match the force density to the conditions at specific sites. The force density represents an incoherent line of vibration force equal to the length of the trains. The unit of force density is force divided by square root of train length, represented here in decibels relative to 1 $lb/(ft)^{1/2}$.

The basic field procedure for at-grade and tunnel testing of transfer mobility is illustrated in Figure 9-1. The goal of the test is to create vibration pulses that travel from the source through the ground to the receiver, using the same path that will be taken by ground-borne vibration from the train. As shown in Figure 9-1, a weight is dropped from a height of 3 to 4 feet onto a load cell, which is calibrated to measure force. Accelerometers are placed on the ground along a line leading away from the point of force application. The responses of the load cell and accelerometers are recorded on a multichannel tape recorder for subsequent analysis in the laboratory.

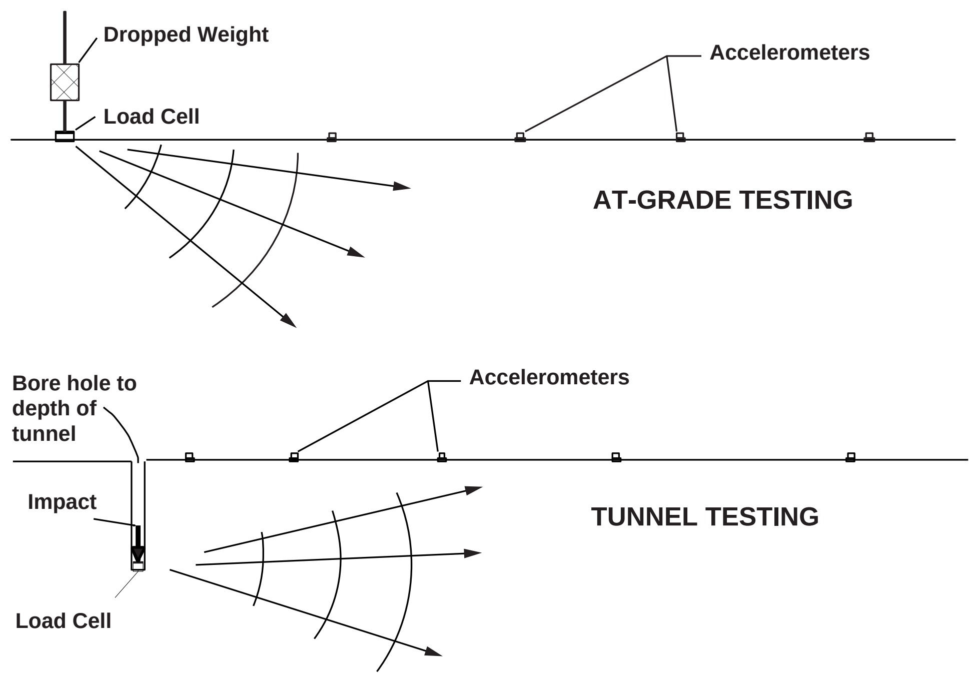

Figure 9-1 Impact Method for Measuring Transfer Mobility

When the procedure is applied to tunnels, the force must be located at the approximate depth of the tunnel. This is done by drilling a bore hole and locating the load cell at the bottom of the hole. The tests are usually performed at the same time that the bore holes are drilled. This allows using the soil-sampling equipment on the drill rig for the transfer mobility testing. The load cell is attached to the bottom of the drill string and lowered to the bottom of the hole. A standard soil sampling hammer, which is usually a 140-lb. weight dropped 18 inches onto a collar attached to the drill string, is used to excite the ground. The load cell must be capable of operating underwater if the water table is near the surface or if a slurry drilling process is used.

Field Procedures

The process of measuring transfer mobility involves impacting the ground and measuring the resulting vibration pulse at various distances from the impact. Two different methods, shown in Figure 9-2, that have been used to estimate equivalent line source transfer mobility from point source transfer mobility are:

1. Lines of transducers: A site is characterized by tests using one or more lines of transducers with the impact at one end of the line. The total length of the line ranges from 150 to 300 feet. Figure 9-2a shows a site being characterized using three lines perpendicular to the rail line. Regression techniques are applied to the 1/3 octave band transfer function data to obtain smooth point-source transfer mobility function curves. Once the point source transfer mobility has been defined, the line source transfer mobility can be calculated using numerical integration techniques (ref. 4). Optimal use of a single borehole can be made by running three or four transducer lines in a radial pattern from each borehole.

2. Lines of impacts: This configuration is shown in Figure 9-2b. One line of transducers is used and the ground is impacted at evenly-spaced intervals along a line perpendicular to the transducer line. Since the impacts represent a train, it is best if the line of impacts can be along the track centerline. When this is not possible, the impact line should parallel the tracks. After the 1/3 octave band point source transfer mobilities are obtained, the equivalent line source transfer mobility is obtained by combining the point source transfer mobilities to approximate a numerical integration. This procedure was used to derive force density functions for X2000, Pendolino, and TGV high speed trains. Recent experience has shown that this approach is more accurate and more repeatable than the first approach. Unfortunately, this approach is usually impractical for tunnels since the ground must be impacted at the bottom of boreholes to approximate propagation from a tunnel structure.

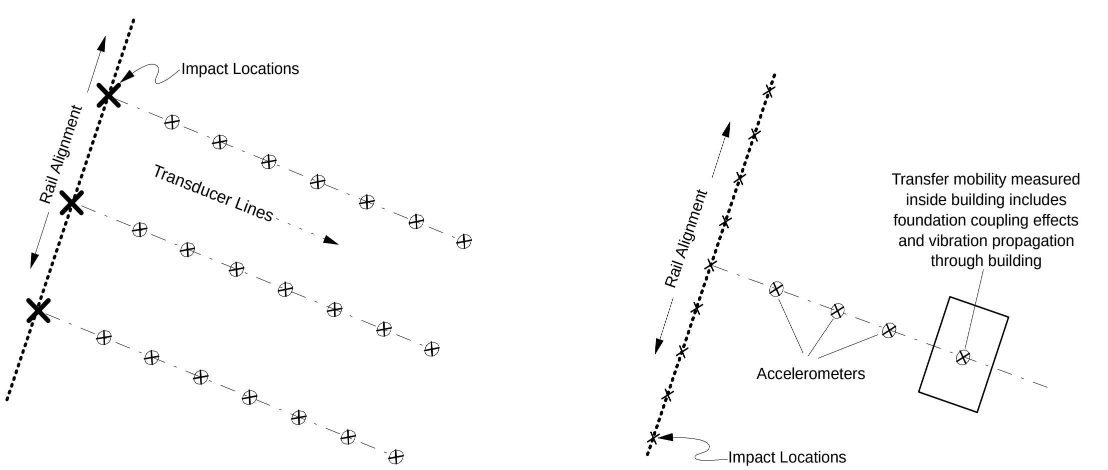

Figure 9.2a Approach 1 for Vibration Propagation Tests

Figure 9.2b Approach 2 for Vibration Propagation Tests

Figure 9-2 Schematic of Two Approaches for Transfer Mobility Measurements

Instrumentation

Performing a vibration propagation test requires specialized equipment. Most of the equipment is readily available from several commercial sources. Commercially available load cells can be used as the force transducer. For borehole testing, the load cells must be hermetically sealed and capable of sustaining impact forces at the bottom of a 30- to 100-foot deep hole partially filled with water. A typical instrumentation array for field testing and laboratory analysis of transfer mobility is shown in Figure 9-3. The force transducer should be capable of impact loads of 5,000 to 10,000 pounds. Either accelerometers or geophones can be used as the vibration transducers. A requirement is that the transducers with associated amplifiers be capable of accurately measuring levels of 0.0001 inches/sec at 40 Hz and have flat frequency response from 6 Hz to 400 Hz. The tape recorder also must have flat response over the 6 to 400 Hz frequency range. Adequate low-frequency response usually requires either an instrumentation-quality FM recorder or a digital recorder. The response of most normal direct-record tape recorders is inadequate at frequencies below about 30 Hz.

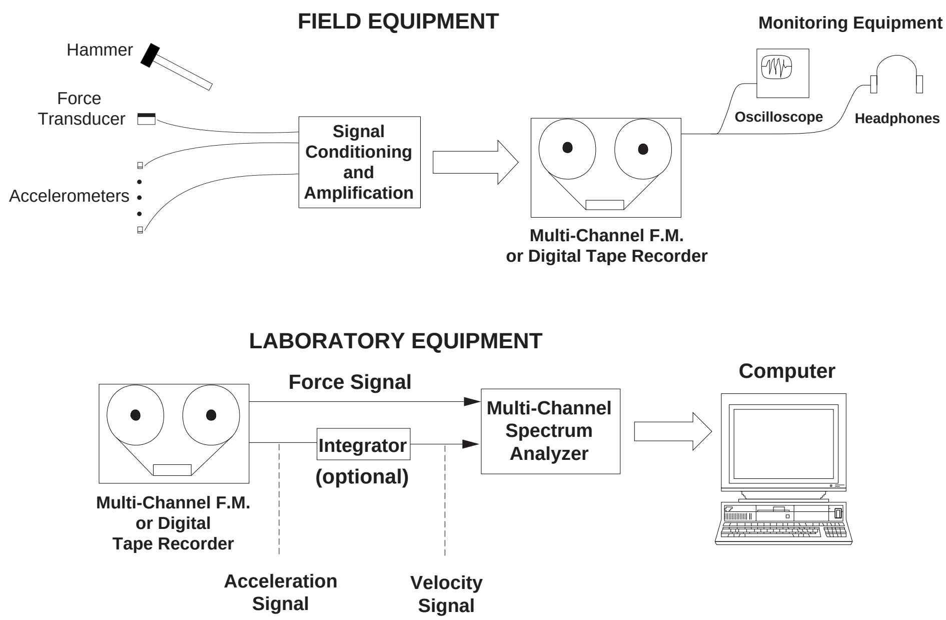

Figure 9-3 Equipment Required for Field Testing and Laboratory Analysis

The narrowband spectrum analyzer is the key element of the laboratory instrumentation. The analyzer must be capable of capturing impulses from at least two channels and calculating the frequency spectrum of the transfer function between the force and vibration channels. All transfer functions should include the average of at least 20 impulses. Averaging more impulses will improve signal enhancement at a rate of 3 dB improvement for each doubling of the number of impacts. Signal enhancement is particularly important when the vibration transducer is more than 100 feet from the impact.

As illustrated in Figure 9-3, the spectrum analyzer usually is interfaced to a computer, which is required to adapt the narrowband transfer function data into a format suitable for evaluating 1/3 octave band transfer mobility. The raw transfer function data usually include several hundred frequency bands. By transforming from narrowband to 1/3 octave band spectra, each spectrum is reduced to 15 to 20 bands. This step reduces the amount of data that must be evaluated to develop the generalized curves. There are specialized multi-channel spectrum analyzers that have built-in capabilities that are sufficient for this data analysis.

Analysis of Transfer Mobility Data

Transfer mobility functions are developed from field measurements in following steps:

Step 1. Analyze the field data to generate narrowband point source transfer mobilities.

Step 2. Calculate 1/3 octave band transfer mobilities at each measurement point from the narrowband results. Because typical spectrum analyzers are not capable of obtaining 1/3 octave band transfer functions, this processing is performed after transferring the data to a computer.

Step 3. Calculate the transfer mobility as a function of distance for each 1/3 octave band.

Step 4. Compute the line source transfer mobility as a function of distance in each 1/3 octave band.

The two field test procedures that have been used to develop estimates of line-source transfer mobility are shown in Figure 9-2. Of the two procedures, the first, involving a single impact point for each line of accelerometers, requires considerably more analysis and professional judgement to develop line source transfer mobility. However, there are some situations where a single impact point is the only practical method to apply.

The steps in developing line-source transfer mobility curves with field data from the first procedure are illustrated in Figure 9-4. The analysis starts with the narrowband transfer function between source and receiver at each measurement position. There should be a minimum of four distances in any test line. Because of the possibility of local variations in propagation characteristics, when feasible, three or more lines should be used to characterize a site. A total of 10 to 20 transducer positions are often used to characterize each site. Assuming that the spectrum analyzer calculates 400 line narrowband transfer functions for each position, a total of 4,000 to 8,000 numbers must be calculated for each site.

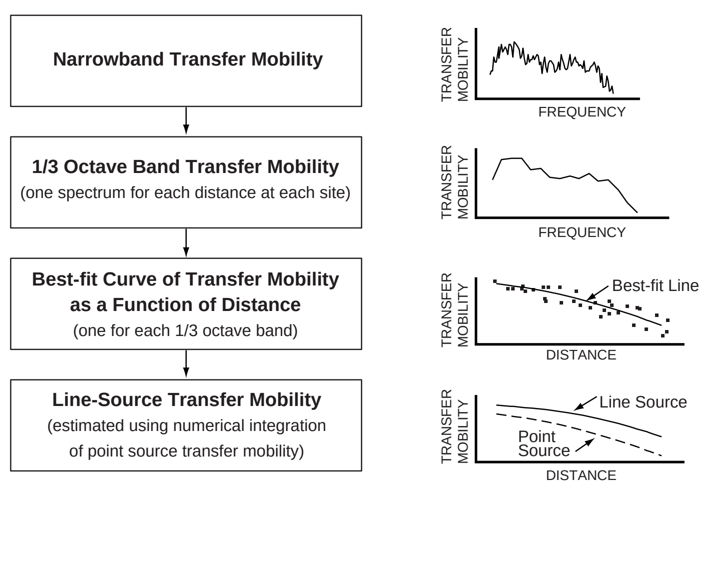

Figure 9-4 Analysis of Transfer Mobility

The next step in the analysis procedure is to calculate the equivalent 1/3 octave band transfer functions. This reduces each spectrum from 400 to 15 numbers. As shown in Figure 9-4, the 1/3 octave band spectrum is much smoother than the narrowband spectrum. The third step is to calculate a best-fit curve of transfer mobility as a function of distance for each 1/3 octave band. When analyzing a specific site, the best-fit curve will be based on 10 to 20 data points. Up to several hundred points could be used to determine average best-fit curves for a number of sites.

The 1/3 octave band best-fit curves can be applied directly to point vibration sources. However, because trains are better represented as line vibration sources, a fourth step is necessary: calculate an equivalent line source transfer mobility using numerical integration.

The analysis involving the second field procedure is slightly different from the first. In this approach, the train is represented by impacts at equally spaced intervals along a line perpendicular to the transducer line. This approach is particularly suited to characterizing a specific building since by placing a transducer inside the building, it is possible to measure line source transfer mobility from the tracks to this point in the building. The resulting transfer mobility combines the vibration path to the building foundation, coupling to the building, and propagation of the vibration energy through the building. This approach can greatly improve the accuracy of projections for that building.

Using the second procedure, a segment of a train can be represented by a line of impact positions along the track centerline at 10- or 20-foot intervals. The 1/3 octave band point source transfer mobilities for each transducer location can then be summed following the trapezoidal rule for numerical integration to directly calculate line-source transfer mobility. The following equation should be used to perform the numerical integration:

$$TM_{line} = 10 \times \log_{10}\left[h \times \left(\frac{10^{\frac{TM_{p_1}}{10}}}{2} + 10^{\frac{TM_{p_2}}{10}} + \ldots + 10^{\frac{TM_{p_{n-1}}}{10}} + \frac{10^{\frac{TM_{p_n}}{10}}}{2} \right) \right]$$

where: h = impact interval,
TM_{pi} = point source transfer mobility for ith impact location, and
n = last impact location.

This approach is considerably more direct than is possible with lines of vibration transducers. An important feature of this approach is that the impact line usually can be shorter, sometimes much shorter than the train. For example, at a distance of 50 feet from a 600-foot train, most of the vibration energy will come for the part of the train closest to the receiver. In this case, the 600-foot train could be accurately modeled using a 200-foot impact line. Judgment must be used in deciding on an appropriate length for the impact line in balancing accuracy of the results, available test conditions in the field, budget, and time constraints.

Deriving Force Density

Force density is not a quantity that can be measured directly. It must be inferred from measurements of transfer mobility and train vibration at the same site. Using a line of impacts to measure line source transfer mobility (developed using the second transfer mobility test procedure) will give the best force density results. The force density for each 1/3 octave band is then simply:

$$L_F = L_v - TM_{line}$$

where: L_F = force density,
L_V = measured train ground-borne vibration, and
Tm_{line} = line source transfer mobility.

The standard approach is to develop force density from the average of measurements at three or more positions.

Trackbed force densities developed from measurements of the TGV, X2000, and Pendolino trains are shown in Figure 9-5. A "worst case" force density that can be used before any information is available on the type of equipment that will be used for a high-speed rail project also is shown in this figure. Adjustments must be made to the force density to account for differences between the facility where the force density was measured and the new system. Guidance for making these adjustments can be found in a U.S. Department of Transportation report.[7]

9.3.4 Vibration and Structure-Borne Noise in Buildings

The propagation of vibration from the building foundation to the receiver room is a very complex phenomenon, dependent on the specific design of the building. Detailed evaluation of the vibration propagation requires extensive use of numerical procedures, such as finite element modeling. An evaluation this detailed generally is not practical for individual buildings considered in this manual. The propagation of vibration through a building and the radiation of sound by vibrating building surfaces consequently is estimated using simple empirical or theoretical models. The recommended procedures are outlined in the *Handbook of Urban Rail Noise and Vibration Control*[8] The approach consists of adding the following adjustments to the 1/3 octave band spectrum of the projected ground-surface vibration:

1. **Building response or coupling loss**. This represents the change in the incident ground-surface vibration due to the presence of the building foundation. The adjustments in the *Handbook* are shown in Figure 9-6. When estimating basement floor vibration or vibration of at-grade slabs the correction is zero.

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[7] J.T. Nelson, H.J. Saurenman, "State-of-the-Art Review: Prediction and Control of Ground-Borne Noise and Vibration from Rail Transit Trains," Report Number UMTA-MA-06-0049-83-4, U.S. Department of Transportation, Urban Mass Transit Administration, December 1983.

[8] H.J. Saurenman, J.T. Nelson, G.P. Wilson, *Handbook of Urban Rail Noise and Vibration Control*, prepared under contract to US DOT/Transportation Systems Center, Report UMTA-MA-06-0099-82-2, February 1982.

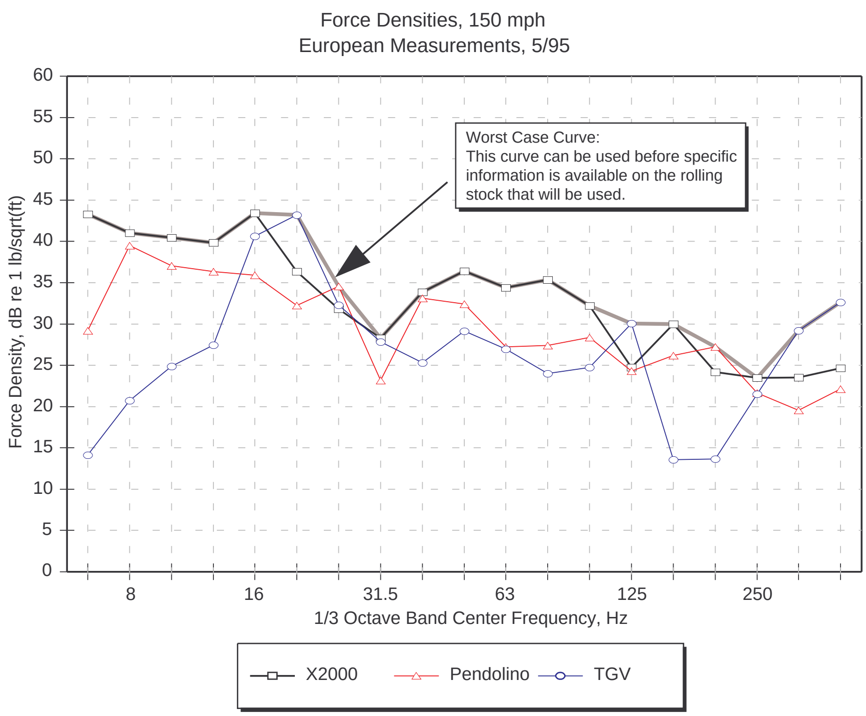

Figure 9-5 Force Densities for High-Speed Trains

2. **Transmission through the building.** The vibration amplitude will decrease as the vibration energy propagates from the foundation through the remainder of the building. The normal assumption is that vibration attenuates by 1 to 2 dB for each floor.

3. **Floor resonances.** Vibration amplitudes will be amplified because of resonances of the floor/ceiling systems. For a typical wood frame residential structure, the fundamental resonance is usually in the 15 to 20 Hz range. Reinforced-concrete slab floors in modern buildings will have fundamental resonance frequencies in the 20 to 30 Hz range. An amplification resulting in a gain of approximately 6 dB should be used in the frequency range of the fundamental resonance.

4. **Radiated noise.** The projected floor vibration is used to estimate the levels of ground-borne noise. The primary factors affecting noise level are the average vibration level of the room surfaces and the amount of acoustical absorption within the room. As discussed above, the radiation adjustment is zero for typical rooms, which gives:

$$L_A \approx L_v + K_{A\text{-}wt}$$

where: L_A = A-weighted sound level in a 1/3 octave band,
L_v = average RMS vibration velocity level, and
$K_{A\text{-}wt}$ = A-weighting adjustment at the center frequency of the 1/3 octave band.

The A-weighted levels in the 1/3 third octave bands are then combined to give the overall A-weighted sound level.

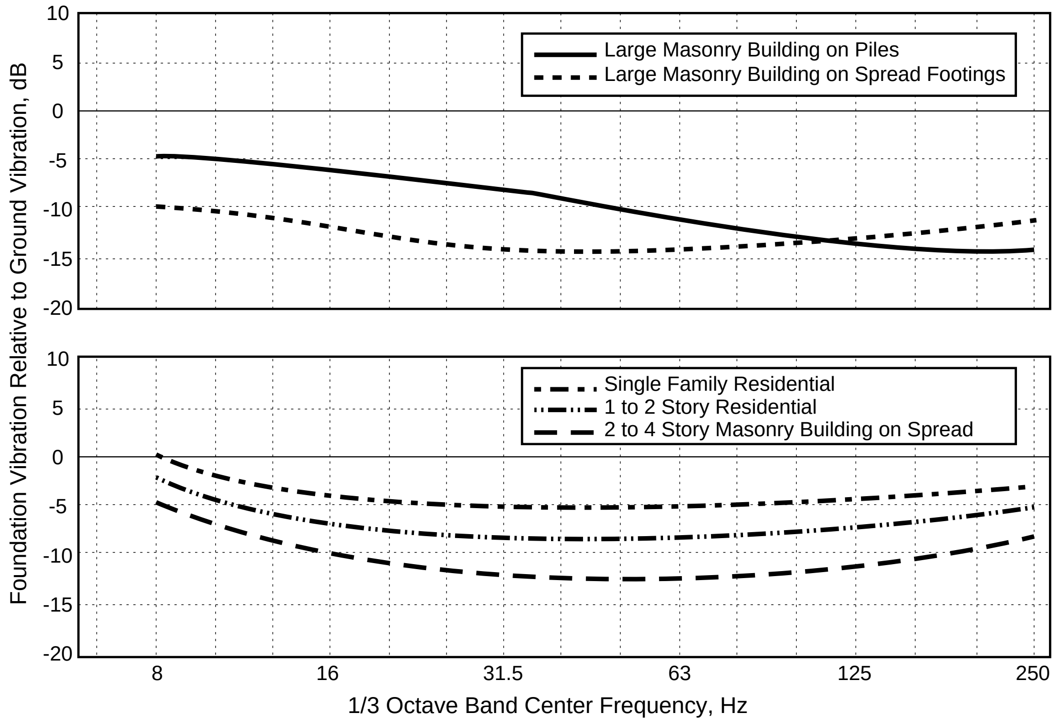

Figure 9-6 Approximate Foundation Response for Various Types of Buildings

9.4 VIBRATION MITIGATION

Mitigation can minimize the adverse effects of project ground-borne vibration on sensitive land uses. Available data indicate that ground-borne vibration from steel-wheel/steel-rail high-speed trains is caused by the same mechanisms as vibration from lower speed trains. Consequently, the approaches to controlling ground-borne vibration from transit systems generally are applicable to high-speed trains.

Because ground-borne vibration is not as common a problem as environmental noise, the mitigation approaches have not been as well defined. In some cases it has been necessary to develop innovative approaches to control the impact. Examples are the floating slab systems that were developed for the Washington, D.C. and Toronto transit systems and wheel-flat detectors that have been used to identify vehicles in need of maintenance.

The importance of adequate wheel and rail maintenance in controlling levels of ground-borne vibration cannot be overemphasized. Problems with rough wheels or rails can increase vibration levels by as much as 20 dB, negating the effects of even the most effective vibration control measures. It is rare that practical vibration control measures will provide more than 15 to 20 dB attenuation. When ground-borne vibration problems are associated with existing rails and rolling stock, often the best control measure is to implement new or improved maintenance procedures. Grinding rough or corrugated rail and implementing wheel truing to restore the wheel surface and contour may reduce vibration more than completely replacing the existing track system with floating slabs.

Assuming that the track and vehicles are in good condition, the options to further reduce ground-borne vibration fit into one of seven categories: (1) maintenance procedures, (2) location and design of special trackwork, (3) vehicle modifications, (4) changes in the track support system, (5) building modifications, (6) adjustments to the vibration transmission path, and (7) operational changes.

Maintenance

As discussed above, effective maintenance programs are essential for keeping ground-borne vibration levels under control. When the wheel and rail surfaces are allowed to degrade, the vibration levels can increase by as much as 20 dB compared to a new or well maintained system. Maintenance procedures that are particularly effective at avoiding increases in ground-borne vibration include:

- Rail grinding on a regular basis, particularly for rail that develops corrugations. Rail condition monitoring systems are available to optimize track conditions.
- Wheel truing to re-contour the wheel, provide a smooth running surface, and remove wheel flats. The most dramatic vibration reduction results from removing wheel flats. However, significant improvements also can be observed simply from smoothing the running surface. Wheel condition monitoring systems are available to optimize wheel conditions.
- Reconditioning vehicles, particularly when components such as suspension system, brakes, and wheels will be improved, and slip-slide detectors will be installed.
- Installing wheel condition monitoring systems to identify those vehicles most in need of wheel truing.

Location and Design of Special Trackwork

Most vibration impact from a new train system is caused by wheel impacts at the special trackwork for turnouts and crossovers. Careful review of crossover and turnout locations during the preliminary engineering stage is an important step in minimizing potential for vibration impact. When feasible, the most effective vibration control measure is to relocate the special trackwork to a less vibration-sensitive area. Sometimes this requires adjusting the location by several hundred feet and will not have a significant adverse impact on the operation plan for the system. Another approach is to install movable-point or spring frogs that eliminate the gaps that occur when standard railbound frogs are used. These special frogs have been shown to significantly reduce vibration levels near crossovers, and they are often specified because of their longer life span under repetitive high-speed conditions.

Vehicle Suspension

The ideal rail vehicle, with respect to minimizing ground-borne vibration, should have a low unsprung weight, a soft primary suspension, a minimum of metal-to-metal contact between moving parts of the truck, and smooth wheels that are perfectly round. A thorough dynamic analysis, including the expected track parameters, should be part of the specifications for any new high-speed trainset.

Special Track Support Systems

When the vibration assessment indicates that vibration levels will be excessive, it is usually the track support system that is modified to reduce the vibration levels. Floating slabs, resiliently supported ties, high resilience fasteners, and ballast mats all have been used to reduce the levels of ground-borne vibration. To be effective, these measures must be optimized for the frequency spectrum of the vibration. These measures have been used successfully on urban transit subway projects, but applications on at-grade and elevated track are rare because: vibration problems are less common for at-grade and elevated track; cost of the vibration control measures is a higher percentage of the construction costs of at-grade and elevated track; and exposure to outdoor weather conditions requires special drainage designs.

The major vibration control measures for track support are discussed below:

- Resilient Fasteners: Resilient fasteners are used to fasten rails to concrete track slabs. Standard resilient fasteners are very stiff in the vertical direction, usually in the range of 200,000 lb/in., although they do provide some vibration reduction. On urban transit systems, special fasteners with vertical stiffness in the range of 40,000 to 75,000 lb/in. have reduced vibration by as much as 5 to 10 dB at frequencies above 30 to 40 Hz.

- Ballast Mats: A ballast mat consists of a rubber or other type of elastomer pad that is placed under the ballast. The mat generally must be placed on a thick concrete or asphalt pad to be effective. It will not be as effective if placed directly on the soil or the sub-ballast. Consequently, most ballast mat applications are in tunnels or bridges. Ballast mats can provide 10 to 15 dB attenuation at frequencies above 25 to 30 Hz. An installation of ballast mat in a tunnel in France near Vouvray in TGV's Atlantique line prevents vibrations from affecting storage and ageing of wines in a nearby wine cave. Ballast mats are often a good retrofit measure for existing tie-and-ballast track where there are vibration problems.

- Resiliently Supported Ties: A resiliently supported tie system, like the one used in the Channel Tunnel between England and France, consists of concrete ties supported by rubber pads. The rails are fastened directly to the concrete ties using standard rail clips. Some measurement data suggest that resiliently supported ties may reduce low-frequency vibration in the 15 to 40 Hz range, which would make them particularly appropriate for rail systems with vibration problems in the 20 to 30 Hz range. The frequency range over which this type of track support system can affect levels of ground-borne vibration depends on the pad stiffness and the interaction between the pads, ties, and rails.

- Floating Slabs: Floating slabs can be very effective at controlling ground-borne vibration and noise. They basically consist of a concrete slab supported on resilient elements, usually rubber or a similar elastomer. A variant that was first used in Toronto and is generally referred to as the double tie system, consists of 5-foot slabs with four or more rubber pads under each slab. Floating slabs are effective at frequencies greater than their single-degree-of-freedom vertical resonance frequency. The floating slabs used in the Washington DC, Atlanta, and Boston transit systems were all designed to have a vertical resonance in the 14 to 17 Hz range. A special London Transport floating slab that is under the Barbican Redevelopment uses a very heavy design with a resonance frequency in the 5 to 10 Hz frequency range.[9] The primary disadvantage of floating slabs is that they tend to be the most expensive of the track-related vibration control treatments.

- Other Treatments: Changing any feature of the track support system can change the levels of ground-borne vibration. Approaches such as using heavier rail, thicker ballast, heavier ties, or resilient elements beneath the tracks can be expected to reduce the vibration levels. There also is some indication that vibration levels are lower with wood ties compared to concrete ties. However, there is little confirmation that any of these approaches will make a significant change in the vibration levels. This is unfortunate since modifications to the ballast, rails, or ties are virtually the only options for typical track systems (at-grade, ballast-and-tie) without resorting to a different type of track support system or widening the right-of-way to provide a buffer zone.

Building Modifications

In some circumstances, it is practical to modify an affected building to reduce the vibration levels. Vibration isolation of buildings basically consists of supporting the building foundation on elastomer pads similar to bridge bearing pads. Vibration isolation is seldom an option for existing buildings. However, building vibration isolation can be particularly important for shared-use facilities such as office space above a train station or terminal. When vibration-sensitive equipment such as electron microscopes will be affected by train vibration, specific modifications to the building structure may be the most cost-effective method of controlling the impact. For example, the floor upon which the vibration-sensitive equipment is located could be stiffened and isolated from the remainder of the building.

Trenches

Use of trenches to control ground-borne vibration is analogous to controlling airborne noise with sound barriers. Although this approach has not received much attention in the U.S., a trench can be a practical method for controlling vibration from at-grade track. A rule-of-thumb given by Richert and Hall[10] is that if the trench is located close to the source, the trench bottom must be at least 0.6 times the Rayleigh wavelength below the vibration source. For most soils, Rayleigh waves travel at around 600 ft/sec, which means that the wavelength at 30 Hz is 20 feet. This means that the trench would have to be approximately 12 feet deep to be effective at 30 Hz.

[9] P. Grootenhuis, "Floating Track Slab Isolation for Railways," *Journal of Sound and Vibration,* 51:3, pp 443-448, 1977.

[10] F. E. Richert and J. R. Hall, *Vibrations of Soils and Foundations*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1970.

A trench can be an effective vibration barrier if it changes the propagation characteristics of the soil. It can be either open or solid. The Toronto Transit Commission did a test with a trench filled with Styrofoam to keep it open. They reported successful performance over a period of at least one year.[11] Solid barriers can be constructed with sheet piling, rows of drilled shafts filled with either concrete or a mixture of soil and lime,[12] or concrete poured into a trench.

Operational Changes

The most obvious operational change is to reduce the vehicle speed. Reducing the train speed by a factor of two will reduce vibration levels approximately 6 dB. Other operational changes that can be effective in special cases are:

- Use the equipment that generates the lowest vibration levels during the nighttime hours when people are most sensitive to vibration and noise.
- Adjust nighttime schedules to minimize train movements during the most sensitive hours.

While there are tangible benefits from reducing speed and limiting operations during the most sensitive time periods, these measures may not be practical from the standpoint of trip time and service frequency requirements. Furthermore, vibration reduction achieved through operating restrictions requires continuous monitoring and will be negated if the signal system does not enforce compliance with the speed restriction.

Buffer Zones

Expanding the rail right-of-way sometimes will be the most economical method of controlling the vibration impact. A similar approach is to negotiate a vibration easement from the affected property owners.

[11] S. T. Lawrence, "TTC-LRT Trackbed Studies, Ground-borne Vibration Testing, Measurement and Evaluation Program," American Public Transit Association Rapid Transit Conference, San Francisco, CA, 1980.

[12] "The Lime Column Method," Report No. 31, Swedish Geotechnical Institute, Linkoping, Sweden, 1994.

Chapter 10

NOISE AND VIBRATION DURING CONSTRUCTION

This chapter discusses the procedures for assessing the temporary noise and vibration impacts associated with the construction of a new high-speed rail facility. Methods for estimating noise and vibration levels from construction equipment using tabulated source levels, as well as procedures for assessing and mitigating potential noise and vibration impacts are provided. While both construction noise and vibration are included in this chapter, there is generally no overlap between them in the methodology and they are covered in separate sections.

Construction often generates community noise/vibration complaints, despite the limited time frame over which it takes place. Complaints typically arise when construction efforts interfere with people's activities, especially when the community has insufficient information about the extent or duration of the construction. Misunderstandings can occur when the contractor is considered insensitive by the community, even though the contractor believes the construction activities are in compliance with local ordinances. This situation underscores the need for early identification and assessment of potential problem areas. An assessment of the potential for complaints can be made by following procedures outlined in this chapter. That assessment can aid contractors in making bids by allowing changes in construction approach and by including mitigation costs before the construction plans are finalized. Publication of an assessment, including a description of the construction noise and vibration environment, can lead to greater understanding and tolerance in the community.

Control of construction noise and vibration occurs in three areas:

- **Assessment:** The environmental impact assessment identifies the potential problem areas during the construction phase of a project and the environmental assessment document informs the public of the project's construction effects. This information is important for new major infrastructure projects where heavy construction can take place over a lengthy period of time. The procedure for performing a noise assessment is discussed in Section 10.1 and for vibration assessment is discussed in Section 10.2.

- **Construction specifications:** Most large construction projects incorporate noise specifications on construction equipment, but sometimes they must include additional measures to minimize community complaints. Special mitigation measures can be written into the construction documents where they are identified as necessary by the environmental impact assessment. The documents should include realistic specifications that lessen community annoyance without unreasonably constraining the contractors. Typical noise limits on equipment are included in Table 10-1.

- **Compliance verification:** Provide clear direction to field inspectors on conducting and reporting measurements for compliance with noise and vibration specifications in sensitive areas.

10.1 CONSTRUCTION NOISE

The noise levels created by operating construction equipment can vary greatly and depend on factors such as the type of equipment, the specific model, the operation being performed, and the condition of the equipment. The equivalent sound level (L_{eq}) of the construction activity also depends on the fraction of time that the equipment is operated over the time period of construction. This section provides information on typical levels generated by various construction equipment and provides guidance on assessment of noise from construction activities related to rail facilities. The level of noise analysis should be commensurate with the type and scale of the project and with the presence of noise-sensitive land uses in the construction zone.

10.1.1 Noise from Typical Construction Equipment and Operations

The dominant source of noise from most construction equipment is the engine, usually a diesel, without sufficient muffling. In a few cases, such as impact pile driving or pavement breaking, noise generated by the action of the machinery dominates.

For purposes of noise assessment, construction equipment can be considered to operate in two modes, stationary and mobile. Stationary equipment operates in one location for one or more days at a time, with either a fixed-power operation (pumps, generators, compressors) or a variable noise operation (pile drivers, pavement breakers). Noise is assumed to emanate from the point of operation. Mobile equipment moves around the construction site with power applied in cyclic fashion (bulldozers, loaders), or to and from the site (trucks). The movement around the site is handled in the construction noise prediction procedure discussed later in this chapter. Variation in power imposes additional complexity in characterizing the noise source level from a piece of equipment. This variation is handled by describing the noise at a reference distance from the equipment operating at full power and adjusting it based on the duty cycle of the activity to determine the L_{eq} of the operation. Standardized procedures for measuring the exterior noise levels for the certification of mobile and stationary construction equipment have been developed by the Society of Automotive Engineers.[1,2] Typical noise levels generated by representative pieces of equipment are listed in Table 10-1. These levels are based on EPA Reports,[3,4,5] measured data from railroad construction equipment, and other measured data.

Construction activities are characterized by variations in the power expended by equipment, with resulting variation in noise levels over time. Variation in power is expressed in terms of the "usage factor" of the equipment, the percentage of time during the workday that the equipment operates at full power. Time-varying noise levels are converted to a single number (L_{eq}) for each piece of equipment during the operation. Besides having daily variations in activities, major construction projects are accomplished in several different phases. Each phase has a specific equipment mix, depending on the work to be accomplished during that phase.

Each phase also has its own noise characteristics; some will have higher continuous noise levels than others, and some have high-impact noise levels. The purpose of the assessment is to determine not only the levels, but also the duration, of the noise. The L_{eq} of each phase is determined by combining the L_{eq} contributions from each piece of equipment used in that phase. The impact and the consequent noise mitigation approaches depend on the criteria to be used in assessing impact, as discussed in the next section.

10.1.2 Construction Noise Assessment

The level of detail in a construction noise assessment depends on the scale and type of project and the stage of environmental review process. Where the project is a major undertaking (the construction duration is expected to last for more than several months, noisy equipment will be involved, and/or the construction is expected to take place near a noise-sensitive site), then construction noise impacts may be determined in considerable detail, as described in this section. For other projects, the assessment may simply be a description of the equipment to be used, the duration of construction, and any mitigation requirements that will be placed on particularly noisy operations.

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[1] Society of Automotive Engineers, "Exterior Sound Level Measurement Procedure for Powered Mobile Construction Equipment," SAE Recommended Practice J88a, 1976.

[2] Society of Automotive Engineers, "Sound Levels for Engine Powered Equipment," SAE Standard J952b, 1976.

[3] U.S. Environmental Protection Agency, "Noise from Construction Equipment and Operations, Building Equipment and Home Appliances," NTID300.1, December 31, 1971.

[4] U.S. Department of Transportation, "Final Environmental Impact Statement, 4(f) Statement; Replacement of Shaw's Cove Bridge and Approaches," FRA-RNC-EIS-80-02-F, September 16, 1981.

[5] William R. Fuller and Ron Brown, "Analysis and Abatement of Highway Construction Noise," EPA 550/9-81-314-A, U.S. Environmental Protection Agency, Office of Noise Abatement and Control and U.S. Department of Transportation, Federal Highway Administration, June 1981.

A construction noise assessment for a major project is performed by comparing the predicted noise levels with criteria established for that type of project. The approach requires an appropriate **descriptor**, a standardized prediction **method**, and a set of recognized **criteria** for assessing the impact.

The descriptor used for construction noise is the L_{eq}. This unit is appropriate for the following reasons:

- It can be used to describe the noise level from operation of each piece of equipment separately and is easily combined to represent the noise level from all equipment operating during a given period.
- It can be used to describe the noise level during an entire phase.
- It can be used to describe the average noise over all phases of the construction.

The recommended method for predicting construction noise impact for major urban transit projects is similar to that suggested by the Federal Highway Administration (FHWA).[6] The FHWA prediction method is used to estimate the construction noise levels associated with the construction of a highway, but it can be used for any transportation project. The method requires:

1. An emission model to determine the noise generated by the equipment at a reference distance.
2. A propagation model that shows how the noise level will vary with distance.
3. A way of summing the noise of each piece of equipment at locations of noise sensitivity.

Table 10-1 Construction Equipment Noise Emission Levels

Equipment	Typical Noise Level (dBA) 50 ft from Source
Air Compressor	81
Backhoe	80
Ballast Equalizer	82
Ballast Tamper	83
Compactor	82
Concrete Mixer	85
Concrete Pump	82
Concrete Vibrator	76
Crane, Derrick	88
Crane, Mobile	83
Dozer	85
Generator	81
Grader	85
Impact Wrench	85
Jack Hammer	88
Loader	85
Paver	89
Pile Driver (Impact)	101
Pile Driver (Sonic)	96
Pneumatic Tool	85
Pump	76
Rail Saw	90
Rock Drill	98
Roller	74
Saw	76
Scarifier	83
Scraper	89
Shovel	82
Spike Driver	77
Tie Cutter	84
Tie Handler	80
Tie Inserter	85
Truck	88

[6] J. A. Reagan and C. A. Grant, "Special Report - Highway Construction Noise: Measurement, Prediction and Mitigation," U.S. Department of Transportation, Federal Highway Administration, 1977.

The first two components of the model are related by the following equation:

$$L_{eq}(equip) = E.L. + 10\log(U.F.) - 20\log\left(\frac{D}{50}\right) - 10\,G\log\left(\frac{D}{50}\right)$$

where:

$L_{eq}(equip)$	=	L_{eq} at a receiver resulting from the operation of a single piece of equipment over a specified time period,
E.L.	=	noise emission level of the particular piece of equipment at the reference distance of 50 feet (taken from Table 10-1),
G	=	constant that accounts for topography and ground effects (taken from Chapter 6, Figure 6-5),
D	=	distance from the receiver to the piece of equipment, and
U.F.	=	usage factor that accounts for the fraction of time that the equipment is in use over the specified time period.

The combination of noise from several pieces of equipment operating during the same time period is obtained from decibel addition of the L_{eq} of each single piece of equipment calculated using this equation.

Major Construction Projects

The assessment of a major construction project can be as detailed as necessary to characterize the construction noise by specifying the various quantities in the equation. For projects in an early assessment stage, when the equipment roster and schedule are undefined, only a rough estimate of construction noise levels is practical.

The following assumptions are adequate for a General Assessment of each phase of construction:

Step 1. **Noise Source Level.** Full power operation for a time period of one hour is assumed because most construction equipment operates continuously for periods of one hour or more at some point in the construction period. Therefore, *U.F.* = 1, and 10 log(*U.F.*) = 0. The emission level at 50 feet, *E.L.*, is taken from Table 10-1. The predictions include only the two noisiest pieces of equipment expected to be used in each construction phase.

Step 2. **Noise Propagation.** Free field conditions are assumed and ground effects are ignored. Consequently, *G* = 0. All pieces of equipment are assumed to operate at the center of the project, or centerline, in the case of a guideway or highway construction project.

A more detailed analysis can be used if warranted, such as when a known noise-sensitive site is adjacent to a construction project or where contractors are faced with stringent local ordinances or specifications as a result of public concern. In such instances, the assessment sequence includes:

Step 1. **Duration of the Construction.** Long-term construction project noise impact is based on a 30-day average L_{dn}, the times of day of construction activity (nighttime noise is penalized by 10 dB in residential areas), and the percentage of time the equipment is to be used during a period of time that will affect *U.F.* For example, an 8-hour L_{eq} is determined by making *U.F.* the percentage of time each individual piece of equipment operates under full power in that period. Similarly, the 30-day average L_{dn} is determined from the *U.F.* expressed by the percentage of time the equipment is used during the daytime hours (7 a.m. to 10 p.m.) and nighttime (10 p.m. to 7 a.m.), separately over a 30-day period. However, to account for increased sensitivity to nighttime noise, the nighttime percentage is multiplied by 10 before performing the computation.

Step 2. **Site topography, natural and constructed barriers, and ground effects.** These features will change the factor *G*. Use Figure 5-3 to calculate *G*.

Step 3. **Refinement of Emission Level.** Measure or certify the emission level of each piece of equipment according to standardized procedures.[7,8] This measurement will refine *E.L.*

Step 4. **Location of Equipment.** Determine the location of each piece of equipment while it is working. The distance factor *D* is therefore specified more exactly.

Step 5. **Total Noise Source Level.** Include all pieces of equipment in the computation of the 8-hour L_{eq} and the 30-day average L_{dn}. The total noise levels are determined using Table 5-5 (Chapter 5).

Minor Construction Projects

Most minor projects need no assessment of construction noise. However, when a construction project over a short period of time occurs in a noise-sensitive area, a qualitative treatment is appropriate. Community relations will be important in this case; early information disseminated to the public about the kinds of equipment, expected noise levels, and durations will help to forewarn potentially affected neighbors about the temporary inconvenience. Helpful information would include a general description of the variation of noise levels during a typical construction day. The General Assessment method described earlier in this section will be sufficient to provide the estimated noise levels. There is no need for a full assessment since the criteria suggested in the following section are not applicable in these cases.

Criteria

No standardized **criteria** have been developed for assessing construction noise impact. Consequently, criteria must be developed on a project-specific basis unless local ordinances apply. Generally, local noise ordinances are not very useful in evaluating construction noise. They usually relate to nuisance and hours of allowed activity and sometimes specify limits in terms of maximum levels, but they are generally not

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[7]Society of Automotive Engineers, "Exterior Sound Level Measurement Procedure for Powered Mobile Construction Equipment," SAE Recommended Practice J88a, 1976.

[8]Society of Automotive Engineers, "Sound Levels for Engine Powered Equipment," SAE Standard J952b, 1976.

practical for assessing the impact of a construction project. Project construction noise criteria should take into account the existing noise environment, the absolute noise levels during construction activities, the duration of the construction, and the adjacent land use. While it is not the purpose of this manual to specify standardized criteria for construction noise impact, the following guidelines can be used as criteria for assessment. They are deliberately conservative because the related assessment method tends to over-predict noise levels. If these criteria are exceeded, the project is likely to face adverse community reaction and steps to mitigate the impact should be evaluated and implemented as necessary.

General Assessment: Identify land uses in the vicinity of the construction project according to residential, commercial, and industrial land use activities. Estimate the combined noise level in one hour from the two noisiest pieces of equipment, assuming they both operate at the same time. Then identify locations where the level exceeds the levels specified in Table 10-2:

Table 10-2 General Assessment Criteria for Construction noise

Land Use	One-hour L_{eq} (dBA)	
	Day	Night
Residential	90	80
Commercial	100	100
Industrial	100	100

Detailed Assessment: Predict the noise level in terms of 8-hour L_{eq} and 30-day averaged L_{dn} and compare to levels specified in Table 10-3:

Table 10-3 Detailed Assessment Criteria for Construction Noise

Land Use	8-hour L_{eq} (dBA)		L_{dn} (dBA)
	Day	Night	30-day Average
Residential	80	70	75[a]
Commercial	85	85	80[b]
Industrial	90	90	85[b]

[a] In urban areas with very high ambient noise levels (L_{dn} > 65 dB), L_{dn} from construction operations should not exceed existing ambient + 10 dB.

[b] Twenty-four-hour L_{eq}, not L_{dn}.

10.1.3 Mitigation of Construction Noise

After using the approach presented in Section 10.1.2 to locate potential impacts from construction noise, the next step is to identify appropriate control measures. The design engineer can implement noise control through layout of the construction site, planning the order of operations, or by choosing less noisy operations. These categories of noise control approaches, with examples of mitigation measures, are given below:

1. Design considerations and project layout:

   - Construct noise barriers, such as temporary walls or piles of excavated material, between noisy activities and noise-sensitive receivers.
   - Route truck traffic away from residential streets, if possible. Select streets with the fewest homes, if no alternatives are available.
   - Site equipment on the construction lot as far away from noise-sensitive sites as possible.
   - Construct walled enclosures around especially noisy activities or around clusters of noisy equipment. For example, shields can be used around pavement breakers and loaded vinyl curtains can be draped under elevated structures .

2. Sequence of operations:

   - Combine noisy operations so they occur in the same time period. The total noise level produced will not be significantly greater than the level produced if the operations were performed separately.
   - Avoid nighttime activities. Sensitivity to noise increases during the nighttime hours in residential neighborhoods.

3. Alternative construction methods:

   - Avoid impact pile driving where possible in noise-sensitive areas. Drilled piles or the use of a sonic or vibratory pile driver are quieter alternatives where the geological conditions permit their use.
   - Use specially quieted equipment, such as quieted and enclosed air compressors, and mufflers on all engines.
   - Select quieter demolition methods, where possible. For example, sawing bridge decks into sections that can be loaded onto trucks results in lower cumulative noise levels than impact demolition by pavement breakers.

The environmental assessment should include a description of one or more mitigation approach for each affected location.

10.2 CONSTRUCTION VIBRATION

Construction activity can result in varying degrees of ground vibration, depending on the equipment and methods employed. Operation of construction equipment causes ground vibrations, which spread through the ground and diminish in strength with distance. Buildings founded on the soil in the vicinity of the construction site respond to these vibrations with varying results, ranging from no perceptible effects at the lowest levels, low rumbling sounds and perceptible vibrations at moderate levels, and slight damage at the highest levels. Ground vibrations from construction activities very rarely reach the levels that can damage structures, but they can achieve the audible and perceptible ranges in buildings very close to the site. A possible exception is construction taking place near old, fragile buildings of historical significance where special care must be taken to avoid damage. The construction vibration criteria should include special consideration for fragile historical buildings. The construction activities that typically generate the most severe vibrations are blasting and impact pile driving.

10.2.1 Vibration Source Levels from Construction Equipment

Various types of construction equipment have been measured operating under a wide variety of construction activities, with an average of source levels reported in terms of velocity levels as shown in Table 10-4. Although Table 10-4 gives one level for each piece of equipment, the reported ground vibration levels from construction activities vary considerably. The data provide a reasonable estimate for a wide range of soil conditions.

Since the primary concern with regard to construction vibration is building damage, construction vibration is generally assessed in terms of peak particle velocity (PPV), as defined in Chapter 6. Peak particle velocity is typically a factor of 2 to 6 times greater than root mean square (rms) vibration velocity; a factor of 4 has been used to calculate the approximate rms vibration velocity levels indicated in Table 10-4.

10.2.2 Construction Vibration Assessment

Construction vibration should be assessed in cases where there is a significant potential for impact from construction activities. Such activities include blasting, pile driving, demolition, and drilling or excavation in close proximity to sensitive structures. The recommended procedure for estimating vibration impact from construction activities is as follows:

Step 1. **Vibration Source Levels.** Select the equipment and associated vibration source levels at the reference distance of 25 feet as shown in Table 10-4.

Step 2. **Vibration Propagation.** Make the propagation adjustment according to the following formula, based on point sources with normal propagation conditions:

$$PPV_{equip} = PPV_{ref} \times \left(\frac{25}{D}\right)^{1.5}$$

where:
- PPV_{equip} = the peak particle velocity in in/sec of the equipment adjusted for distance
- PPV_{ref} = the reference vibration level in in/sec at 25 feet from Table 10-4, and
- D = the distance from the equipment to the receiver.

Step 3. Damage Criterion. Apply the PPV vibration damage threshold criterion of 0.50 in/sec (approximately 102 VdB) for fragile buildings, or 0.12 in/sec (approximately 90 VdB) for extremely fragile historic buildings.[9]

Step 4. Annoyance Criterion. For considerations of annoyance or interference with vibration-sensitive activities, estimate the RMS vibration level L_v at any distance D from the following equation:

$$L_v(D) = L_v(25\text{ ft}) - 20\log\left(\frac{D}{25}\right)$$

Apply the vibration impact criteria in Chapter 7 for vibration-sensitive sites.

Table 10-4 Vibration Source Levels for Construction Equipment
(From measured data.[10,11,12,13])

Equipment		PPV at 25 ft (in/sec)	Approximate L_v† at 25 ft
Pile Driver (impact)	upper range	1.518	112
	typical	0.644	104
Pile Driver (vibratory)	upper range	0.734	105
	typical	0.170	93
Clam shovel drop (slurry wall)		0.202	94
Hydromill (slurry wall)	in soil	0.008	66
	in rock	0.017	75
Large bulldozer		0.089	87
Caisson drilling		0.089	87
Loaded trucks		0.076	86
Jackhammer		0.035	79
Small bulldozer		0.003	58

† RMS velocity in decibels (VdB) re 1 μinch/second

[9]Swiss Consultants for Road Construction Association, "Effects of Vibration on Facilities," VSS-SN640-312a, Zurich, Switzerland, April 1992.

[10]D.J. Martin, "Ground Vibrations from Impact Pile Driving during Road Construction," Supplementary Report 544, United Kingdom Department of the Environment, Department of Transport, Transport and Road Research Laboratory, 1980.

[11]J.F. Wiss, "Vibrations During Construction Operations," Journal of Construction Division, Proc. American Society of Civil Engineers, 100, No. CO3, pp. 239 - 246, September 1974.

[12]J.F. Wiss, "Damage Effects of Pile Driving Vibrations," Highway Research Record, No. 155, Highway Research Board, 1967.

[13]D.A. Towers, "Ground-borne Vibration from Slurry Wall Trench Excavation for the Central Artery/Tunnel Project Using Hydromill Technology," Proceedings of Inter-Noise 95, Newport Beach, CA, July 1995, pp. 227 - 232.

10.2.3 Construction Vibration Mitigation

After using the procedure described in Section 10.2.2 to locate potential impacts (or damage) from construction vibrations, the next step is to identify control measures. Similar to construction noise, mitigation of construction vibration requires consideration of equipment location and processes, as follows:

1. <u>Design considerations and project layout:</u>
   - Route heavily loaded trucks away from residential streets, if possible. Select streets with fewest homes, if no alternatives are available.
   - Operate earthmoving equipment on the construction lot as far away from vibration-sensitive sites as possible.

2. <u>Sequence of operations:</u>
   - Phase demolition, earthmoving, and ground-impacting operations so as not to occur in the same time period. Unlike noise, the total vibration level produced could be significantly less when each vibration source operates separately.
   - Avoid nighttime activities. People are more aware of vibration in their homes during the nighttime hours.

3. <u>Alternative construction methods:</u>
   - Avoid impact pile driving where possible in vibration-sensitive areas. Drilled piles or the use of a sonic or vibratory pile driver causes lower vibration levels where the geological conditions permit their use.
   - Select demolition methods not involving impact, where possible. For example, sawing bridge decks into sections that can be loaded onto trucks results in lower vibration levels than impact demolition by pavement breakers, and milling generates lower vibration levels than excavation using clam shell or chisel drops.
   - Avoid vibratory rollers and packers near sensitive areas.

10.2.4 Special Note on Pile Driving

Pile driving is potentially the greatest source of vibration associated with equipment used during construction of a project. The source levels in Table 10-4 indicate that vibratory pile drivers may provide substantial reduction of vibration levels. However, the additional vibration effects of vibratory pile drivers may limit their use in sensitive locations. A vibratory pile driver operates by continuously shaking the pile at a fixed frequency, literally vibrating it into the ground. However, continuous operation at a fixed frequency may be more noticeable to nearby residents, even at lower vibration levels. Furthermore, the steady-state excitation of the ground may increase resonance response of building components. Resonant response may be unacceptable in cases of fragile historical buildings or vibration-sensitive manufacturing processes. Impact pile drivers, on the other hand, produce a high vibration level for a short time (0.2 seconds) with sufficient time between impacts to allow any resonant response to decay.

Chapter 11

DOCUMENTATION OF NOISE AND VIBRATION ASSESSMENT

To be effective, noise and vibration analyses must be presented to the public in a clear, comprehensive manner. The mass of technical data and information necessary to withstand scrutiny in the environmental review process must be documented in a manner that remains intelligible to the public. Justification for all assumptions used in the analysis, such as selection of representative measurement sites and all baseline conditions, must be presented for review. For large-scale projects, the environmental document normally contains a condensation of essential information to maintain a reasonable size. For these projects, separate technical reports are usually prepared as supplements to the Environmental Impact Statement (EIS) or Environmental Assessment (EA). For smaller projects, or ones with minimal noise or vibration impact, all the technical information may be presented in the environmental document itself. This chapter gives guidance on how the necessary noise and vibration information should be incorporated in the project's environmental documentation.

11.1 THE TECHNICAL REPORT ON NOISE AND VIBRATION

A separate technical report is often prepared as a supplement to the environmental document (EIS or EA). A technical report is appropriate when all of the data cannot be placed in the environmental document. The details of the analysis are important for establishing the basis for the assessment. Consequently, all the details in the technical report should be contained in a well-organized format for easy access to the information. While the technical report is not intended to be a primer on the subject, the technical data and descriptions should be presented in a manner that can be understood by the general public. All the necessary background information should be included in the technical report, including tables, maps, charts, drawings, and references that may be too detailed for the environmental document, but that are important in helping to draw conclusions about the project's noise and vibration impacts and mitigation options.

11.1.1 Organization of Technical Report

The technical report on noise and vibration should contain the following major subject headings, along with the key information content described below. If both noise and vibration have been analyzed, it is generally preferable to separate the noise and vibration sections; as shown in this manual, the approaches to the two topics are quite different.

Overview – This section contains a brief description of the project and an overview of the noise/vibration concerns. It sets forth the initial considerations in framing the scope of the study.

Inventory of Noise and Vibration-Sensitive Sites – The approach for selecting noise/vibration- sensitive sites should be described in sufficient detail to demonstrate completeness. Sites and site descriptions are to be included.

Measurements of Existing Noise and Vibration Conditions – The basis for selecting measurement sites should be documented, along with tables of sites coordinated with maps showing locations of sites. If the measurement data are used to estimate existing conditions at other locations, the rationale and the method should be included. Measurement procedures should be fully described. Tables of measurement instruments should include manufacturer, type, serial number, and date of most recent calibration by authorized testing laboratory. Measurement periods, including time of day and length of time at each site, should be shown to demonstrate adequate representation of the ambient conditions. The measurement data should be presented in well-organized form in tables and figures. A summary and interpretation of measured data should be included.

Special Measurements Related to the Project – Some projects may require specialized measurements at sensitive sites, such as outdoor-to-indoor noise level reduction of homes or transmission of vibrations into concert halls and recording studios. Other projects may need special source level characterization. Full descriptions of the measurements and the results should be included.

Predictions of Noise/Vibration from the Project – The prediction model used for estimating future project conditions should be fully described and referenced. Any changes or extensions to the models recommended in this manual should be fully described so that the validity of the adjustments can be confirmed. Specific data used as input to the models should be listed. Computed levels should be tabulated and illustrated by contours, cross-sections, or shaded mapping. It is important to illustrate noise and vibration impacts with base maps at a scale with enough detail to provide location reference for the reader.

Noise and Vibration Criteria – Impact criteria for the project should be fully described and referenced (refer to Chapters 3 and 8). In addition, any applicable local ordinances should be described. Tables specifying the criteria levels also should be included. If the project involves considerable construction, and a separate construction noise and vibration analysis will be included, then construction criteria should appear in a separate section with its own assessment.

Noise and Vibration Impact Assessment – The impact assessment should be described according to the procedures outlined in this manual. A resulting impact inventory should be presented for each alternative mode or alignment to enable ready comparison among alternatives. The inventory should be tabulated according to the different types of land uses affected. The results of the assessment may be presented both before and after mitigation.

Noise and Vibration Mitigation – The mitigation section of the report should begin with a summary of all treatments considered, even if some are not carried to final consideration. Final candidate mitigation treatments should be considered separately, with description of the features of the treatment, costs, expected benefit in reducing impacts, locations where the benefit would be realized, and discussion of practicality of implementing alternative treatments. Enough information should be included to allow the project sponsor and FRA to reach decisions on mitigation prior to issuance of the final environmental document.

Construction Noise and Vibration Impacts – Criteria adopted for construction noise or vibration should be described, if appropriate. In accordance with Chapter 10, these may be adopted on a project-specific basis. The method used for predicting construction noise or vibration should be described, along with inputs to the models, such as equipment roster by construction phase, equipment source levels, assumed usage factors, and other assumed site characteristics. The predicted levels should be shown for sensitive sites and short-term impacts should be identified. Feasible abatement methods should be discussed in enough detail such that construction contract documents could include mitigation measures.

References – Documentation is an important part of the validation of the technical report. References should be provided for all criteria, approaches and data used in the analyses, including other reports related to the project which may be relied on for information, e.g., geotechnical reports.

11.2 THE ENVIRONMENTAL DOCUMENT

The environmental document typically includes noise and vibration information in three places: a section of the chapter on the affected environment (existing conditions) and two sections in the chapter on environmental consequences (long-term and short-term impacts). The noise and vibration information presented in the environmental document is a summary of the comprehensive information from the technical report, with emphasis on presenting the salient points of the analysis in a format and style that affected property owners and other interested citizens can understand. Smaller projects may have all of the technical information contained within the environmental document; special care should be taken in summarizing technical details to convey the information adequately.

The environmental document provides full disclosure of noise and vibration impacts, including identification of locations where impacts cannot be mitigated satisfactorily. An EIS describes significant impacts and tells what the federal agency intends to do about them. Issuing a Finding of No Significant Impact (FONSI) may depend on mitigation being included. The specific mitigation recommendation in the environmental document depends on the stage of project development and the stage of environmental review. For example, a Draft EIS may discuss different options to mitigate noise or vibration, deferring the final selection of measures to the Final EIS. It may be particularly important to present mitigation options at an early stage, especially if there is a benefit in receiving input from the public on the choices.

The final environmental document (Final EIS or FONSI) can take two approaches to describe any decisions on whether and/or how to mitigate. The document could describe the actual mitigation measures that will be employed, along with the reductions in noise or vibration expected to occur. In this case, the report should include language making it clear that the measures shall be implemented if the project is approved. However, in some cases, mitigation measures may still be under study in the environmental review and will not be selected until the final design stage. In such cases, the final environmental document should express a commitment to mitigate impacts that are verified during final design. Mitigation in these cases can be addressed in the form of a "performance standard" to be met by using one or more of the measures under study.

11.2.1 Organization of Noise and Vibration Sections

Chapter on Affected Environment (Existing Conditions)

This chapter describes the pre-project setting, including the existing noise and vibration conditions, that will likely be affected by one or more of the alternatives. The primary function of this chapter is to establish the focus and baseline conditions for later chapters discussing environmental impacts. Consequently, this chapter is a good place to put basic information on noise and vibration descriptors and effects, as well as for describing the characteristics in the vicinity of the project. Again, it is preferable to separate the noise and vibration sections.

- **Description of Noise and Vibration Descriptors, Effects and Typical Levels:** Information from Chapters 2 and 7 of this manual can be used to provide a background for the discussions of noise/vibration levels and characteristics to follow. Illustrative material to guide the reader in understanding typical levels is helpful.
- **Inventory of Noise and Vibration-Sensitive Sites:** The approach for selecting noise and vibration-sensitive sites should be described in sufficient detail to demonstrate completeness. Sites and site descriptions are to be included.
- **Noise and Vibration Measurements:** A summary of the site selection procedure should be included, along with tables of sites coordinated with maps showing locations of sites. The measurement approach should be summarized, with justification for the measurement procedures used. The measurement data should be presented in well-organized form in tables and figures. To save space, the results are often included with the table of sites described above. In some cases, measurements may be supplemented or replaced by collected data relevant to the noise and vibration characteristics of the area. For example, soils information for estimating ground-borne vibration propagation characteristics may be available from other projects in the area. Fundamental to this section are a summary and interpretation of how the collected data define the project setting.

Chapter on Environmental Consequences.

The section on long-term impacts, the impacts due to operation of the project, should be organized according to the following order:

1. **Overview of Approach.** A summary of the assessment procedure for determining noise and vibration impacts is provided as a framework for the following sections.

2. **Estimated Noise and Vibration Levels.** A general description of prediction models used to estimate project noise/vibration levels should be provided. Any distinguishing features unique to the project, such as source levels associated with various technologies, should be described. The results of the predictions for various alternatives should be described in general terms first, followed by a detailed accounting of predicted noise levels. This information should be supplemented with tables and illustrated by contours, cross-sections or shaded mapping. If contours are included in a technical report, then it is not necessary to repeat them here.

3. **Criteria for Noise and Vibration Impact.** Impact criteria for the project should be fully described and referenced (refer to Chapters 3 and 7). In addition, any applicable local ordinances should be described. Tables listing the criterion levels should be included.

4. **Impact Assessment.** The impact assessment can be a section by itself, or it can be combined with the criteria section. It is important to provide a description of locations where noise and vibration impact is expected to occur without implementation of mitigation measures, based on the predicted future levels, existing levels and the criteria for impact. Inventory tables of impacted land uses should be used to quantify the impacts for comparisons among alternatives. The comprehensive list of noise- and vibration-sensitive sites identified in the Affected Environment chapter should be included in this inventory table.

5. **Noise and Vibration Mitigation.** Perhaps the most significant difference between the technical report and the environmental document is in the area of mitigation. Whereas the technical report discusses options and may make recommendations, the environmental document provides the vehicle for reaching decisions on appropriate mitigation measures, with consideration given to environmental benefits, feasibility, and cost. This section should begin with a summary of all noise and vibration mitigation measures considered for the impacted locations. The specific measures selected for implementation should be fully described. However, for projects where technical details of the mitigation measures cannot be specified at the environmental assessment stage, a commitment is made to the level of abatement; the EIS must demonstrate that mitigation measures under consideration will achieve the necessary reduction. FRA strongly encourages noise abatement for projects where impacts are identified. Reasons for dismissing any abatement measures should also be clearly stated, especially if such non-implementation results in significant adverse effects. The expected benefits for each treatment in reducing impact should be given for each location.

6. **Unavoidable Adverse Environmental Effects.** If it is projected that adverse noise and vibration impacts will result after all reasonable abatement measures have been incorporated, the impacts should be identified in this section.

Impacts During Construction

The environmental document may have a separate section on short-term impacts due to project construction, depending on the scale of the project. For a major project there may be a special section on construction noise and vibration impacts; this section should be organized according to the comprehensive outline described above. For projects with relatively minor effects, a briefer format should be used, with a section included in the chapter on Environmental Consequences.

APPENDIX A
BACKGROUND – NOISE CONCEPTS

A.1 NOISE METRICS

Environmental noise generally derives from a conglomeration of distant noise sources. Such sources may include distant traffic, wind in trees, and distant industrial or farming activities, all part of our daily lives. These distant sources create a low-level "background noise" in which no particular individual source is identifiable. Background noise is often relatively constant from moment to moment, but varies slowly from hour to hour as natural forces change or as human activity follows its daily cycle. Superimposed on this low-level, slowly varying background noise is a succession of identifiable noisy events of relatively brief duration. These events may include single-vehicle passbys, aircraft flyovers, screeching of brakes, and other short-term events, all causing the noise level to fluctuate significantly from moment to moment.

It is possible to describe these fluctuating noises in the environment using single-number descriptors. To do this allows manageable measurements, computations, and impact assessment. The search for adequate single-number noise descriptors has encompassed hundreds of attitudinal surveys and laboratory experiments, plus decades of practical experience with many alternative descriptors.

A.1.1 A-weighted Level: The Basic Noise Unit

As discussed in Chapter 2, the basic noise unit for environmental noise is the A-weighted sound level. It describes the magnitude of noise at a receiver at any moment in time and is read directly from noise-measuring equipment, with the "weighting switch" set on "A." Typical A-weighted sound levels from high-speed rail systems as well as other outdoor and indoor sources are shown in Figure 2-2.

Typical community A-weighted sound levels range from the 30s to the 90s, where 30 is very quiet and 90 is very loud. A-weighted sound level measured in *decibels* is abbreviated "dBA," where the "dB" stands for decibels and refer to the general strength of the noise. The decibel is a unit that can be used to denote the ratio between any two quantities that are proportional to power. When used to describe sound level, the number of decibels is 10 times the logarithm (to the base 10) of the ratio (p^2/p_{ref}^2), where p is the sound pressure (in micropascals) and p_{ref} is a reference pressure (20 micropascals). The letter "A" indicates that the sound has been filtered to reduce the strength of very low and very high-frequency sounds, much as the human ear does. Without this A-weighting, noise-monitoring equipment would respond to events people cannot hear, events such as high-frequency dog whistles and low-frequency seismic disturbances. On the average, each A-weighted sound level increase of 10 decibels corresponds to an approximate doubling of subjective loudness.

A-weighted sound levels are adopted here as the basic noise unit because: (1) they can be easily measured, (2) they approximate the human ear's sensitivity to sounds of different frequencies, (3) they match attitudinal-survey tests of annoyance better than do other basic units, (4) they have been in use since the early 1930s, and (5) they are endorsed as the proper basic unit for environmental noise by nearly every agency concerned with community noise throughout the world.

This manual uses the following single-number descriptors for environmental noise measurements, computations, and assessment:

The *A-weighted Sound Level*, which describes a receiver's noise level at any moment in time.

The *Maximum Level* (L_{max}) during a single noise event.

The *Sound Exposure Level (SEL)*, which describes a receiver's cumulative noise exposure from a single noise event.

The *Hourly Equivalent Sound Level* ($L_{eq}(h)$), which describes a receiver's cumulative noise exposure from all events over a one-hour period.

The *Day-Night Sound Level* (L_{dn}), which describes a receiver's cumulative noise exposure from all events over a full 24 hours, with events between 10 p.m. and 7 a.m. increased by 10 decibels to account for greater nighttime sensitivity to noise.

The following sections illustrate all of these noise descriptors, in turn, and describes their particular application in this manual. Graphic illustrations and mathematical definitions are provided to help the reader understand and see the interrelationships among descriptors.

A.1.2 Maximum Level (L_{max}) During a Single Noise Event

As a train approaches, passes by, and then proceeds into the distance, the A-weighted sound level rises, reaches a maximum, and then fades into the background noise. The maximum A-weighted sound level reached during this passby is called the Maximum Level, abbreviated here as "L_{max}." For noise compliance tests of transient sources, such as moving rail vehicles under controlled conditions with smooth wheel and rail conditions, L_{max} is typically measured with the sound level meter's switch set on "fast," meaning that the sound level is averaged over a period of 0.125 seconds. Another use of L_{max} (fast), abbreviated $L_{max,f}$, is for identifying defective components such as wheel flat spots in a passing train or an excessively noisy car in a long consist of freight cars. However, for tests of continuous or stationary sources, and for describing short-term noise events for the general assessment of noise impact, it is usually more appropriate to use the "slow" setting, where the sound level is averaged over a 1 second period. When set on "slow," sound level meters ignore some of the very-transient fluctuations, which are unimportant to people's overall assessment of the noise. L_{max} (slow), abbreviated $L_{max,s}$ gives a better representation of sound energy of an event and is therefore more directly related to the sound exposure level (SEL) described in the next subsection.

Measurements reported as L_{max} without designation of "fast" or "slow" meter response often become a source of confusion, which leads to errors in interpretation. Measurements of high-speed trains to obtain reference levels for this manual consistently showed $L_{max,f}$ to be 2 dB higher than $L_{max,s}$. Therefore, in general, if it is important to document the sound level of a very short-term event, less than one second in duration, use the "fast" meter setting; otherwise, use "slow." The manner in which the L_{max} descriptor fits into the time history of environmental noise is shown in Figure A-1.

A.1.3 SEL: The Cumulative Exposure from a Single Noise Event

The quantitative measure of the noise "dose" for single noise events is the Sound Exposure Level, abbreviated here as "SEL". The fact that SEL is a cumulative measure means that (1) louder events have higher SELs than quieter ones, and (2) events that last longer in time have higher SELs than shorter ones. People react to the duration of noise events, judging longer events to be more annoying than shorter ones, assuming equal maximum A-Levels. The Sound Exposure Level is computed as:

$$SEL = 10\log\begin{bmatrix}\text{total sound energy}\\ \text{during the event}\end{bmatrix}$$

A more specific mathematical definition is:

$$SEL = 10\log\left[\int_{-\infty}^{\infty} 10^{L_A(t)/10}\, dt\right]$$

where $L_A(t)$ represents the time-varying A-weighted sound level during an event. Time base is assumed to be one second.

SEL is used in this manual as the measure of each single high-speed train event because unlike L_{max},

- SEL increases with the duration of a noise event, which is important to people's reaction,
- SEL therefore allows a uniform assessment method for differing high-speed rail technologies, and
- SEL can be used to calculate the one-hour and 24-hour cumulative descriptors discussed below.

A.1.4 Hourly Equivalent Sound Level [L_{eq}(h)]

The descriptor for cumulative one-hour exposure is the Hourly Equivalent Sound Level, abbreviated here as "L_{eq}(h)." It is an hourly measure that accounts for the moment-to-moment fluctuations in A-weighted sound levels due to all sound sources during that hour, combined. Sound fluctuation is illustrated in the upper frame of Figure A-1 for a single noise event such as a train passing on nearby tracks. As the train approaches, passes by, and then proceeds into the distance, the A-weighted Sound Level rises, reaches a maximum, and then fades into the background noise. The area under the curve in this upper frame is the receiver's noise exposure over this five-minute period.

The center frame of Figure A-1 shows sound level fluctuations over a one-hour period that includes the five-minute period from the upper frame. The area under the curve represents the noise exposure for one hour. The Hourly Equivalent Sound Level is computed as:

$$L_{eq}(hour) = 10\ \log_{10}\begin{bmatrix}\text{Total sound energy}\\ \text{during one hour}\end{bmatrix} - 35.6$$

or mathematically:

$$L_{eq}(hour) = 10\log_{10}\left[\frac{1}{T}\int_{t_1}^{t_2} 10^{L_A(t)/10}\,dt\right]$$

where the one-hour interval extends from t_1 to t_2, and $T = t_2 - t_1 = 1$ hour. The constant 35.6 is obtained from time normalization: one hour = 3600 seconds, and 10 log 3600 = 35.6.

Sound energy is totaled here over a full hour; thus, it accumulates from all noise events during that hour. Subtraction of 35.6 from the total sound energy during one hour in the first equation converts it into a time average, as does the $1/T$ factor shown in the second equation. In brief, if the actual fluctuating noise were replaced by a constant noise equal to this average value, the receiver would be exposed to the same total noise energy. This type of average value is "equivalent" in that sense to the actual fluctuating noise.

A useful, alternative way of computing L_{eq} due to a series of high speed rail noise events is:

$$L_{eq}(hour) = 10\ \log_{10}\begin{bmatrix}\text{Energy Sum of}\\ \text{all SELs}\end{bmatrix} - 35.6$$

or mathematically:

$$L_{eq}(hour) = 10\log_{10}\left[\frac{1}{T}\sum_{i} 10^{SEL_i/10}\right]$$

This equation concentrates on the cumulative contribution of individual noise events, and is the fundamental equation incorporated into Chapters 4 and 5.

The bottom frame of Figure A-1 shows the sound level fluctuations over a full 24-hour period. It is discussed in Section A.1.5.

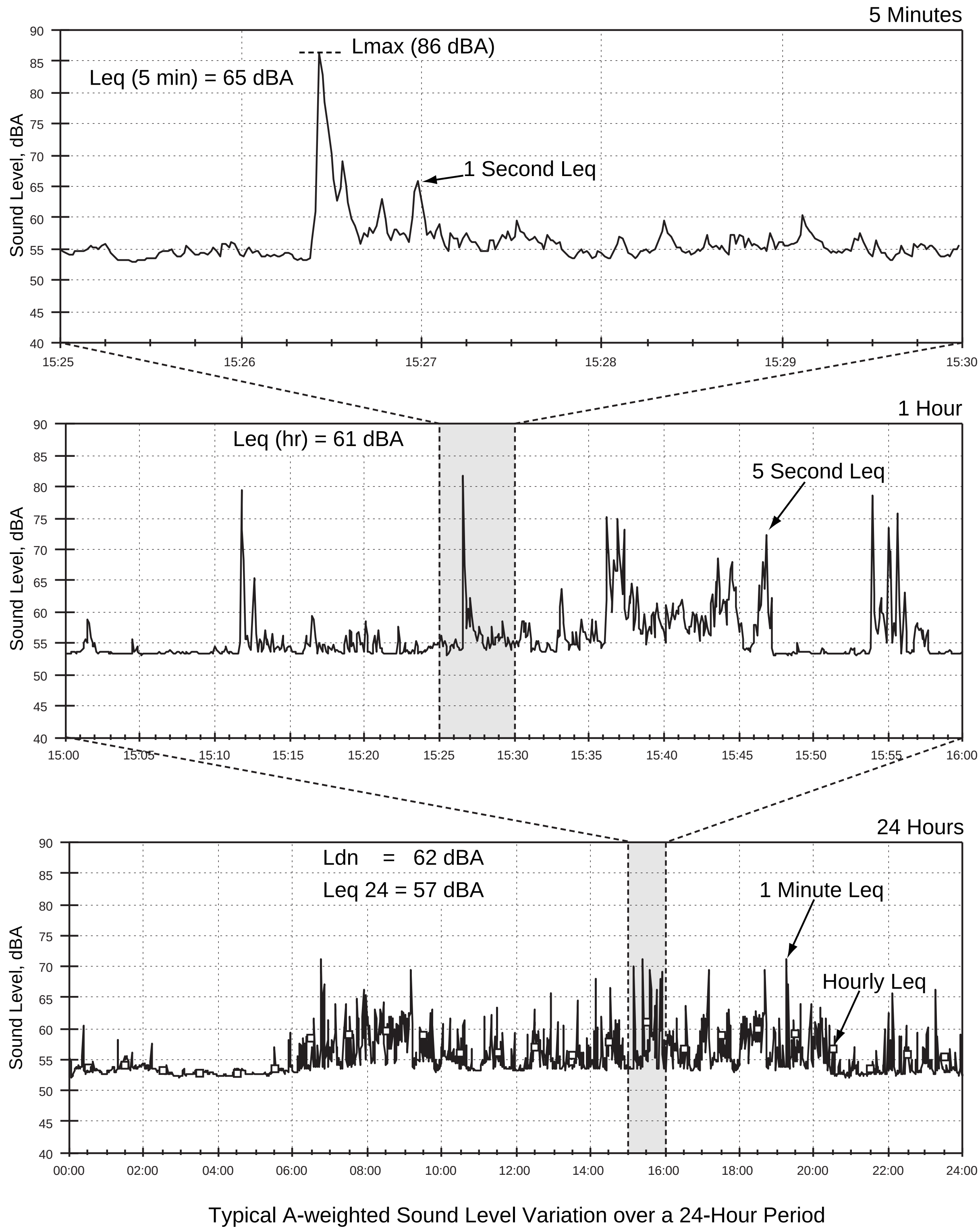

Figure A-1 Example A-Weighted Sound Level Time Histories

Typical hourly L_{eq}'s, both for high-speed rail and non-high-speed rail sources, are shown in Figure A-2. These L_{eq}'s depend upon the number of events during the hour and also upon each event's duration, which is affected by speed. Doubling the number of events during the hour will increase the L_{eq} by 3 decibels, as will doubling the duration of each individual event.

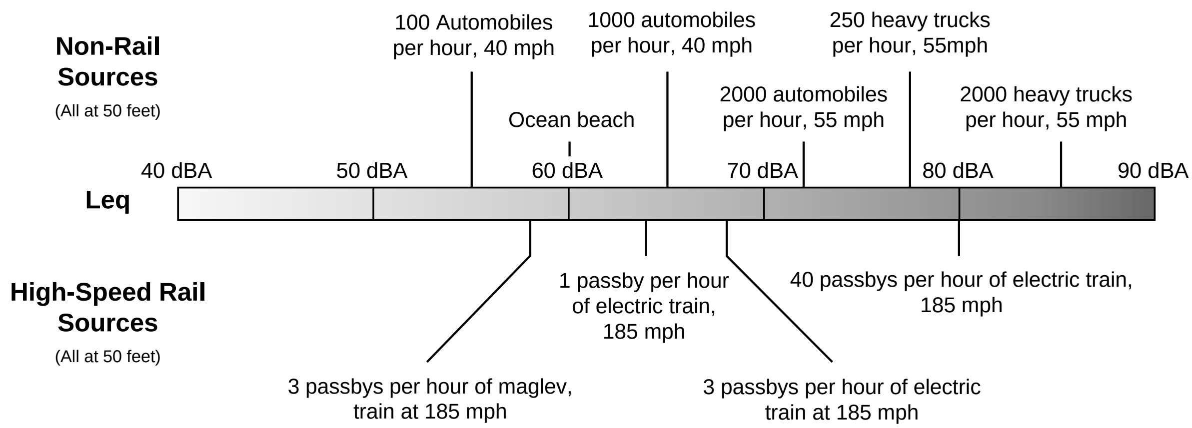

Figure A-2 Typical Hourly L_{eq}'s

Hourly L_{eq} is adopted as the measure of cumulative noise impact for non-residential land uses (those not involving sleep) because:

- L_{eq}'s correlate well with speech interference in conversation and on the telephone – as well as interruption of TV, radio, and music enjoyment,
- L_{eq}'s increase with the duration of events, which is important to people's reaction,
- L_{eq}'s take into account the number of events over the hour, which is also important to people's reaction, and
- L_{eq}'s are used by the Federal Highway Administration in assessing highway-traffic noise impact.

Thus, this noise descriptor can be used to compare and contrast modal alternatives such as highway versus rail. L_{eq} is computed for the loudest facility hour during noise-sensitive activity at each particular non-residential land use.

A.1.5 Day-Night Sound Level (L_{dn}): The Cumulative 24-Hour Exposure from All Events

The descriptor for cumulative 24-hour exposure is the Day-Night Sound Level, abbreviated as "L_{dn}." It is a 24-hour measure that accounts for the moment-to-moment fluctuations in A-Levels due to all sound sources during 24 hours, combined. Such fluctuations are illustrated in the bottom frame of Figure A-1. The area under the curve represents the receiver's noise exposure over a full 24 hours. Some vehicle passbys occur at night in the figure, when the background noise is less. Mathematically, the Day-Night Level is computed as:

$$L_{dn} = 10\log_{10}\begin{bmatrix}\text{Total sound energy}\\ \text{during 24 hours}\end{bmatrix} - 49.4$$

where nighttime noise (10 p.m. to 7 a.m.) is increased by 10 decibels before totaling. The constant 49.4 is obtained from the time normalization: 24 hours = 86,400 seconds, and 10 log 86,400 = 49.4.

Sound energy is totaled over a full 24 hours; it accumulates from all noise events during that 24 hours. Subtraction of 49.4 from this 24-hour exposure converts it into a type of "average." If the actual fluctuating noise were replaced by a constant noise equal to this average value, the same total noise exposure would enter the receiver's ears.

An alternative way of computing L_{dn} from 24 hourly L_{eq}'s is:

$$L_{dn} = 10\log_{10}\begin{bmatrix}\text{Energy sum of}\\ \text{24 hourly } L_{eq}s\end{bmatrix} - 13.8$$

where nighttime L_{eq}'s are increased by 10 decibels before totaling, as in the previous equation.

This is expressed mathematically as:

$$L_{dn} = 10\log_{10}\left[\frac{\sum_{hour=7am}^{10pm} 10^{L_{eq}(hour)/10} + \sum_{hour=10pm}^{7am} 10^{L_{eq}(hour)+10/10}}{24}\right]$$

where:

the 15-hour period from 7:00 am to 10:00 pm is defined as daytime (unweighted), and
the 9-hour period 10:00 pm to 7:00 am is defined as nighttime (with 10-decibel weighting).

L_{dn} due to a series of high-speed train events can also be computed as:

$$L_{dn} = 10\log_{10}\begin{bmatrix}\text{Energy sum of}\\ \text{all SELs}\end{bmatrix} - 49.4$$

Use of this equation assumes that train noise dominates the 24-hour noise exposure. Here again, nighttime SELs are increased by 10 decibels before totaling. This last equation concentrates upon individual noise events, and is the equation incorporated into Chapters 4 and 5.

Typical L_{dn}'s, both for high-speed rail and conventional transit sources are shown in Figure A-3. As shown in the figure, typical L_{dn}'s range from the 50s to the 70s – where 50 is a quiet 24-hour period and 70 is an extremely noisy one. These L_{dn}'s depend upon the number of events during day and night separately – and also upon each event's duration, which is affected by vehicle speed.

L_{dn} is adopted as the measure of cumulative noise impact for residential land uses (those involving sleep), because:

- L_{dn} correlates well with the results of attitudinal surveys of residential noise impact,
- L_{dn} increases with the duration of transit events, which is important to people's reaction,
- L_{dn} takes into account the number of transit events over the full 24 hours, which is also important to people's reaction,
- L_{dn} takes into account the increased sensitivity to noise at night, when most people are asleep,
- L_{dn} allows composite measurements to capture all sources of community noise combined,
- L_{dn} allows quantitative comparison of transit noise with all other community noises,
- L_{dn} is the designated metric of choice of other Federal agencies such as Federal Transit Administration (FTA), Department of Housing and Urban Development (HUD), Federal Aviation Administration (FAA), and Environmental Protection Agency (EPA), and
- L_{dn} has wide international acceptance.

In terms of individual passbys, some characteristics of both the L_{eq} and the L_{dn} are as follows:

When passby L_{max}'s increase:	→ Both L_{eq} and L_{dn} increase,
When passby durations increase:	→ Both L_{eq} and L_{dn} increase,
When the number of passbys increases:	→ Both L_{eq} and L_{dn} increase,
When some operations shift to louder vehicles:	→ Both L_{eq} and L_{dn} increase, and
When passbys shift from day to night:	→ L_{dn} increases.

All of these increases in L_{eq} and L_{dn} correlate to increases in community annoyance.

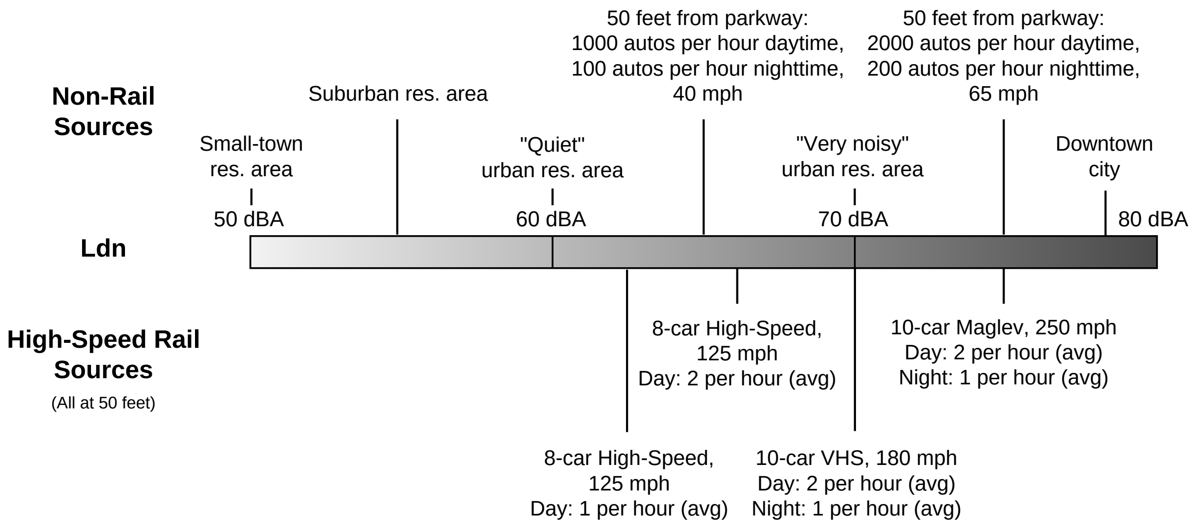

Figure A-3 Typical L_{dn}'s

A.1.6 Other Descriptors

As discussed in Chapter 2, there are a number of international descriptors for transportation noise seldom used in the U.S. The most widely encountered such descriptor, particularly in describing noise from rail systems, is the A-weighted "passby level," or $L_{Aeq,P}$.[1] This descriptor is used to quantify the noise level from a single vehicle passby, and is defined as the A-weighted sound level energy-averaged over the time of the event passby. In a sense, it is like L_{eq}(hour), except that it is evaluated for only a single event and averaged over the event-specific passby time instead of a standardized time period. It is defined mathematically as follows:

$$L_{Aeq,P} = 10\log_{10}\left[\frac{1}{T_p}\int_{t_1}^{t_2} 10^{L_A(t)/10}\,dt\right]$$

where:

t_1 is the time at the leading edge of the passby,
t_2 is the time at the trailing edge of the passby, and
the passby duration $T_p = t_2 - t_1$.

[1] Also sometimes abbreviated $L_{p,p}$ and L_{max}(mean).

In Japan a similar metric is used to describe the noise from train passages, L_{Amax}, and is defined as the power- or energy-average of the "slow" maximum level ($L_{max,s}$) of 20 consecutive train passbys. Mathematically this is expressed as:

$$L_{Amax} = 10\log_{10}\left[\frac{1}{20}\sum_{i=1}^{20} 10^{(L_{max,s})_i/10}\right]$$

A metric known as Sound Exposure Level, but abbreviated L_{AE}, also is used in Japan and has a slightly different definition from the SEL used in this manual. It is defined as the energy-averaged value of the sound exposure, or energy during the event, measured within 10 dB of L_{Amax}, sampled at a time interval of 5/3 seconds. The mathematical expression is:

$$L_{AE} = 10\log_{10}\left[\sum_{i} \Delta t \cdot 10^{L_{Ai}/10}\right]$$

where Δt = 5/3 seconds.

A.2 RECEIVER RESPONSE TO TRANSPORTATION NOISE

An overview of receiver response to noise is presented in this section. It serves as background information for the noise impact criteria presented in Chapter 3 and for the criteria development process documented in Section A.3.

Noise can interrupt ongoing activities and can result in community annoyance, especially in residential areas. In general, most residents become highly annoyed when noise interferes significantly with activities such as sleeping, talking, noise-sensitive work, and listening to radio or TV or music. In addition, some land uses, such as outdoor concert pavilions, are inherently incompatible with high noise levels.

Annoyance to noise has been investigated and approximate exposure-response relationships have been quantified by the Environmental Protection Agency (EPA).[2,3] The selection of noise descriptors in this manual is largely based upon this EPA work. Beginning in the 1970s, EPA undertook a number of research and synthesis studies relating to community noise of all types. Results of these studies have been widely published, and discussed and referenced by many professionals in acoustics. Basic conclusions of these studies have been adopted by the Federal Interagency Committee on Noise, the Department of

[2]Environmental Protection Agency, "Impact Characterization of Noise Including Implications of Identifying and Achieving Levels of Cumulative Noise Exposure," Task group 3, Henning von Gierke, Chairman, Report NTID 73.4, Washington DC, 27 July 1973.

[3]Environmental Protection Agency, "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," Report No. 550/9-74-004, Washington DC, March 1974.

Housing and Urban Development (HUD), the American National Standards Institute, and even internationally.[4,5,6,7] Conclusions from this seminal EPA work remain scientifically valid to this day.

A synthesis of actual case studies of community reaction to newly introduced sources of noise in a residential urban neighborhood is shown in Figure A-4 (ref. 3). The new noise's excess above existing noise levels is shown in Figure A-4. Both the new and existing noise levels are expressed as Day-Night Sound Levels, L_{dn}, discussed in Section A.1.5. The community reaction to this newly introduced noise also is shown in Figure A-4, varying from "No Reaction" to "Vigorous Action," for newly introduced noises averaging from "10 decibels below existing" to "25 decibels above existing." Note that these data points apply only when the stated assumptions are true. For other conditions, the points shift to the right or left somewhat.

In a large number of community attitudinal surveys, transportation noise has been ranked among the most significant causes of community dissatisfaction. A synthesis of many such surveys on annoyance appears in Figure A-5.[8,9] Different neighborhood noise exposures are plotted horizontally. The percentage of people who are *highly annoyed* by their particular level of neighborhood noise is plotted vertically. As shown in the figure, the percentage of high annoyance is approximately 0 at 45 decibels, 10 percent around 60 decibels and increases quite rapidly to approximately 70 percent around 85 decibels. The scatter about the synthesis line is due to variation from community to community and to some wording differences in the various surveys. A recent update of the original research, containing several additional railroad, transit and street traffic noise surveys, confirmed the shape of the original Schultz curve.[10]

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[4] Federal Interagency Committee on Urban Noise, "Guidelines for Considering Noise in Land Use Planning and Control," a joint publication of the Environmental Protection Agency, the Department of Transportation, the Department of Housing and Urban Development, the Department of Defense, and the Veterans Administration, Washington DC, June 1980.

[5] Department of Housing and Urban Development, "Environmental Criteria and Standards of the Department of Housing and Urban Development," 24 Code of Federal Regulations Part 51; 44 Federal Register 40861, Washington DC, 12 July 1979.

[6] American National Standards Institute, "American National Standard: Compatible Land Use With Respect to Noise," Standard S3.23-1980, New York NY, May 1980.

[7] International Standards Organization, "Assessment of Noise with Respect to Community Response," Recommendation R-1996, Geneva, 1971.

[8] T.J. Schultz, "Noise Rating Criteria for Elevated Rapid Transit Structures," U.S. Department of Transportation Report No. UMTA-MA-06-0099-79-3, Washington DC, May 1979.

[9] T. J. Schultz, "Synthesis of Social Surveys on Noise Annoyance," Journal of the Acoustical Society of America, Vol. 63, No. 8, August 1978.

[10] S. Fidell, D.S. Barber, and T.J. Schultz, "Updating a Dosage-Effect Relationship for the Prevalence of Annoyance Due to General Transportation Noise," Journal of the Acoustical Society of America, Vol. 89, No. 1, January 1991.

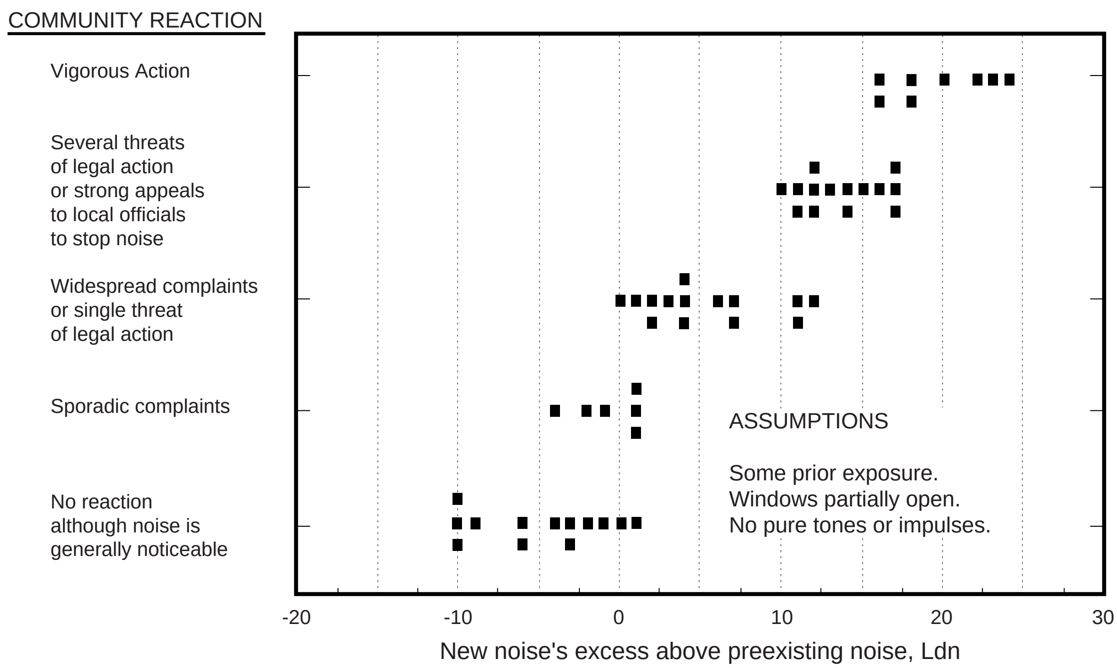

Figure A-4 Community Reaction to New Noise, Relative to Existing Noise in a Residential Urban Environment

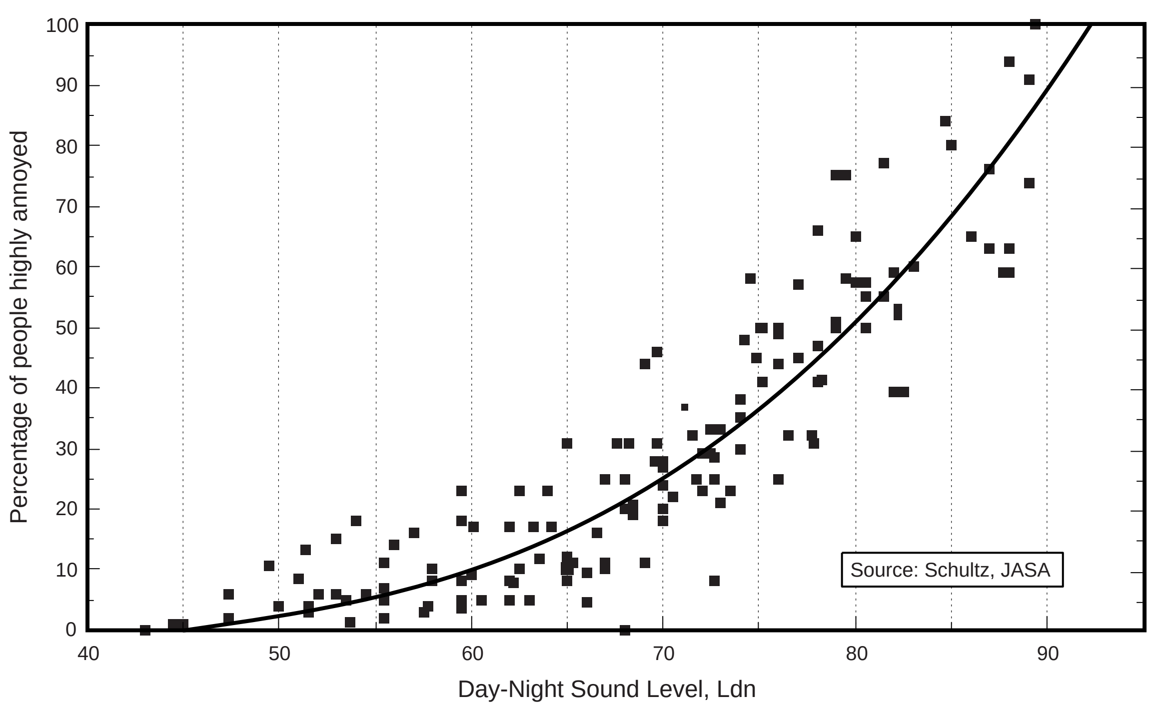

Figure A-5 Community Annoyance Due to Noise

As indicated by these two figures, introduction of high-speed rail noise into a community may have two undesirable effects. First, it may significantly increase existing noise levels in the community, levels that residents have mostly become accustomed to. This effect is called "relative" noise impact. Evaluation of this effect is "relative" to existing noise levels; relative criteria are based upon noise increases above existing levels. Second, newly-introduced noise may interfere with community activities, independent of existing noise levels; it may be simply too loud to converse or to sleep. This effect is called "absolute" noise impact, because it is expressed as a fixed level not to be exceeded and is independent of existing noise levels. Both of these effects, relative and absolute, enter into the assessment of noise impact discussed in Chapters 4 and 5. These two types of impact, relative and absolute, are merged into the noise criteria described in Chapter 3.

A.3 NOISE IMPACT CRITERIA DEVELOPMENT

The noise criteria presented in Chapter 3 of this manual have been developed based on well-documented criteria and research into human response to community noise. The primary goals in developing these noise criteria were to ensure that the impact limits be firmly founded in scientific studies, be realistically based on noise levels associated with high-speed rail projects, and represent a reasonable balance between community benefit and project costs. This section provides the background information.

A.3.1 Relevant Literature

An annotated list of the documents that are particularly relevant to the noise impact criteria follows:

1. US Environmental Protection Agency "Levels Document" (ref. 3): This report identifies noise levels consistent with the protection of public health and welfare against hearing loss, annoyance, and activity interference. It has been used as the basis of numerous community noise standards and ordinances.

2. CHABA Working Group 69, "Guidelines for Preparing Environmental Impact Statements on Noise":[11] This report was the result of deliberations by a group of leading acoustical scientists with the goal of developing a uniform national method for noise impact assessment. Although the CHABA's proposed approach has not been adopted, the report serves as an excellent resource documenting research in noise effects. It provides a strong scientific basis for quantifying impacts in terms of L_{dn}.

3. "Synthesis of Social Surveys on Noise Annoyance" (ref. 9): In 1978, Theodore J. Schultz, an internationally known acoustical scientist, synthesized the results of a large number of social surveys, each concerning annoyance due to transportation noise. Remarkable consistency was found in a group of these surveys, and the author proposed that their average results be taken as the

[11] National Academy of Sciences, "Guidelines for Preparing Environmental Impact Statements on Noise," Report from Committee on Bioacoustics and Biomechanics (CHABA) Working Group 69, February 1977.

best available prediction of transportation noise annoyance. This synthesis has received essentially unanimous acceptance by acoustical scientists and engineers. The "universal" transportation response curve developed by Schultz (Figure A-5) shows that the percent of the population highly annoyed by transportation noise increases from 0 at an L_{dn} of approximately 50 dBA to 100 percent when L_{dn} is about 90 dBA. Most significantly, this curve indicates that for the same increase in L_{dn}, there is a greater increase in the number of people highly annoyed at high noise levels than at low noise levels. In other words, a 5 dB increase at low ambient levels (40 - 50 dB) has less impact than at higher ambient levels (65 - 75 dB). A recent update of the original research, containing several railroad, transit and street traffic noise surveys, confirmed the shape of the original Schultz curve (ref. 10).

4. HUD Standards:[12] The U.S. Department of Housing and Urban Development (HUD) has developed noise standards, criteria and guidelines to ensure that housing projects supported by HUD achieve the goal of a suitable living environment. The HUD site acceptability standards define 65 dB (L_{dn}) as the threshold for a normally unacceptable living environment and 75 dB (L_{dn}) as the threshold for an unacceptable living environment.

5. French High Speed Rail Noise Survey:[13] The first comprehensive high-speed rail noise annoyance survey was performed along the route of TGV Atlantique south of Paris. Surveys of residents along the dedicated high-speed rail line were conducted before and after operation of the trains. Results of the study led to recommendations that the noise assessment descriptor be modified to include early morning and nighttime events and that a procedure be developed for noise assessment of multi-modal operations. Both of these objectives are included in the development of criteria for this manual.

A.3.2 Basis for Noise Impact Criteria Curves

The lower curve in Figure 3-1, representing the onset of Impact, is based on the following considerations:

- The EPA finding that a community noise level of L_{dn} less than or equal to 55 dBA is "requisite to protect public health and welfare with an adequate margin of safety" (ref. 2).
- The conclusion by EPA and others that a 5 dB increase in L_{dn} or L_{eq} is the minimum required for a change in community reaction.
- The research finding that there are very few people highly annoyed when the L_{dn} is 50 dBA, and that an increase in L_{dn} from 50 dBA to 55 dBA results in an average of 2 percent more people highly annoyed (see Figure A-5).

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[12] U.S. Department of Housing and Urban Development, "Environmental Criteria and Standards", 24 Code of Federal Regulations Part 51, 12 July 1979; amended by 49 FR 880, 6 January 1984.

[13] J. Lambert, Pl Champelovier, I. Vernet, "Annoyance from high speed train noise: a social survey," Journal of Sound and Vibration, 193(1), 1996.

Consequently, the change in noise level from an existing ambient level of 50 dBA to a cumulative level of 55 dBA caused by a project is assumed to be a minimal impact. Expressed another way, this is considered to be the lowest threshold where impact starts to occur. Moreover, the 2 percent increment represents the minimum measurable change in community reaction. Thus the curve's hinge point is placed at a project noise level of 53 dBA and an existing ambient noise level of 50 dBA, the combination of which yields a cumulative level of 55 dBA. The remainder of the lower curve in Figure 3-1 was determined from the annoyance curve (Figure A-5) by allowing a fixed 2 percent increase in annoyance at other levels of existing ambient noise. As cumulative noise increases, it takes a smaller and smaller increment to attain the same 2 percent increase in highly annoyed people. While it takes a 5 dB noise increase to cause a 2 percent increase in highly annoyed people at an existing ambient noise level of 50 dB, an increase of only 1 dB causes the 2 percent increase of highly annoyed people at an existing ambient noise level of 70 dB.

The upper curve delineating the onset of Severe Impact was developed in a similar manner, except that it was based on a total noise level corresponding to a higher degree of impact. The Severe Noise Impact curve is based on the following considerations:

- The Department of Housing and Urban Development (HUD) in its environmental noise standards defines an L_{dn} of 65 as the onset of a normally unacceptable noise zone (ref. 7). Moreover, the Federal Aviation Administration (FAA) considers that residential land uses are not compatible with noise environments where L_{dn} is greater than 65 dBA [14].
- The common use of a 5 dBA increase in L_{dn} or L_{eq} as the minimum required for a change in community reaction.
- The research finding that the foregoing step represents a 6.5 percent increase in the number of people highly annoyed (see Figure A-5).

Consequently, the increase in noise level from an existing ambient level of 60 dBA to a cumulative level of 65 dBA caused by a project represents a change from an acceptable noise environment to the threshold of an unacceptable noise environment. This is considered to be the level at which Severe Impact starts to occur. Moreover, the 6.5 percent increment represents the change in community reaction associated with Severe Impact. Thus the upper curve's hinge point is placed at a project noise level of 63 dBA and existing ambient noise level of 60 dBA, the combination of which yields a cumulative level of 65 dBA. The remainder of the upper curve in Figure 3-1 was determined from the annoyance curve (Figure A-5) by fixing the increase in annoyance for all existing ambient noise levels at 6.5 percent.

Both curves incorporate a maximum limit for the high-speed rail project noise in noise-sensitive areas. Independent of existing noise levels, Impact for land use categories 1 and 2 is considered to occur whenever the <u>high-speed rail</u> L_{dn} equals or exceeds 65 dBA and Severe Impact occurs whenever the <u>high-</u>

[14] U.S. Department of Transportation, Federal Aviation Administration, "Federal Aviation Regulations Part 150: Airport Noise Compatibility Planning," January 1981.

speed rail L_{dn} equals or exceeds 75 dBA. These absolute limits are intended to restrict activity interference caused by the project alone.

Both curves also incorporate a maximum limit for cumulative noise increase at low existing noise levels (below about 45 dBA). This is a conservative measure that reflects the lack of social survey data on people's reaction to noise at such low ambient levels. Similar to the FHWA approach in assessing the relative impact of a highway project, the transit noise criteria include caps on noise increases of 10 dBA and 15 dBA for Impact and Severe Impact, respectively, relative to the existing noise level.

Finally, due to the types of land use included in Category 3, the criteria allow the project noise for Category 3 sites to be 5 decibels greater than for Category 1 and Category 2 sites. This difference is reflected by the offset in the vertical scale on the right side of Figure 3-1. With the exception of active parks, which are clearly less sensitive to noise than Category 1 and 2 sites, Category 3 sites include primarily indoor activities and thus the criteria reflect the noise reduction provided by the building structure.

A.3.3 Equations for Noise Impact Criteria Curves

The noise impact criteria can be quantified through the use of mathematical equations that approximate the curves shown in Figure 3-1. These equations may be useful when performing the noise assessment methodology through the use of spreadsheets, computer programs, or other analysis tools. Otherwise, such mathematical detail is generally not necessary to properly implement the criteria, and direct use of Figure 3-1 is likely to be adequate and less time-consuming.

A total of four continuous curves are obtained from the criteria: two threshold curves ("Impact" and "Severe Impact") for Category 1 and 2; and two for Category 3. Note that for each level of impact, the overall curves for Categories 1 and 2 are offset by 5 dBA from Category 3. While each curve is graphically continuous, it is defined by a set of three discrete equations that represent three "regimes" of existing noise exposure. These equations are approximately continuous at the transition points between regimes.

The first equation in each set is a linear relationship, representing the portion of the curve in which the existing noise exposure is low and the allowable increase is capped at 10 dBA and 15 dBA for Impact and Severe Impact, respectively. The second equation in each set represents the impact threshold over the range of existing noise exposure for which a fixed percentage of increase in annoyance is allowed, as described in the previous section. This curve, a third-order polynomial approximation derived from the Schultz curve, covers the range of noise exposure encountered in most populated areas and is used in determining noise impact for most transit projects. Finally, the third equation in each of the four sets represents the absolute limit of project noise imposed by the criteria, for areas with high existing noise exposure. For land use categories 1 and 2, this limit is 65 dBA for Impact and 75 dBA for Severe Impact. For land use category 3, the limit is 70 dBA for Impact and 80 dBA for Severe Impact.

The four sets of equations corresponding to the curves are given below. Each curve represents a threshold of noise impact, with impact indicated for points on or above the curve.

Threshold of Impact:

$$L_P = \begin{cases} 11.450 + 0.953\,L_E & L_E < 42 \\ 71.662 - 1.164\,L_E + 0.018\,L_E^{\,2} - 4.088\times10^{-5}\,L_E^{\,3} & 42 \le L_E \le 71 \\ 65 & L_E > 71 \end{cases} \quad \text{Category 1 and 2}$$

$$L_P = \begin{cases} 16.450 + 0.953\,L_E & L_E < 42 \\ 76.662 - 1.164\,L_E + 0.018\,L_E^{\,2} - 4.088\times10^{-5}\,L_E^{\,3} & 42 \le L_E \le 71 \\ 70 & L_E > 71 \end{cases} \quad \text{Category 3}$$

Threshold of Severe Impact:

$$L_P = \begin{cases} 17.322 + 0.940\,L_E & L_E < 44 \\ 96.725 - 1.992\,L_E + 3.02\times10^{-2}\,L_E^{\,2} - 1.043\times10^{-4}\,L_E^{\,3} & 44 \le L_E \le 77 \\ 75 & L_E > 77 \end{cases} \quad \text{Category 1 and 2}$$

$$L_P = \begin{cases} 22.322 + 0.940\,L_E & L_E < 44 \\ 101.725 - 1.992\,L_E + 3.02\times10^{-2}\,L_E^{\,2} - 1.043\times10^{-4}\,L_E^{\,3} & 44 \le L_E \le 77 \\ 80 & L_E > 77 \end{cases} \quad \text{Category 3}$$

where:

L_E is the existing noise exposure in terms of L_{dn} or L_{eq}(h), and
L_P is the project noise exposure which determines impact, also in terms of L_{dn} or L_{eq}(h).

A.4 STARTLE EFFECTS FROM RAPID ONSET RATES

Researchers report that sounds of approaching vehicles with rapidly rising sound signatures carry a sense of convergence and cause greater annoyance than receding sounds.[15]

A.4.1 High-Speed Rail Noise Signatures

The presence of a high-speed rail system in close proximity to homes may result in a new noise unlike other existing sources of community noise. The sound signature at a position close to a high-speed train passby is characterized by sudden onset of high noise levels for a short duration. A typical example is shown in Figure A-6, where the sound rises rapidly at 15 dB per second and falls again within approximately five seconds. Shorter trains, such as the two-car test train of the German TransRapid TR07, can have even faster onset rates and shorter durations.

[15] G. Rosinger, D.W. Nixon, and H.E. vonGierke. "Quantification of the Noisiness of 'Approaching' and 'Receding' Sounds," J.Acoust. Soc. Am., 48, pp.843-853, October 1970.

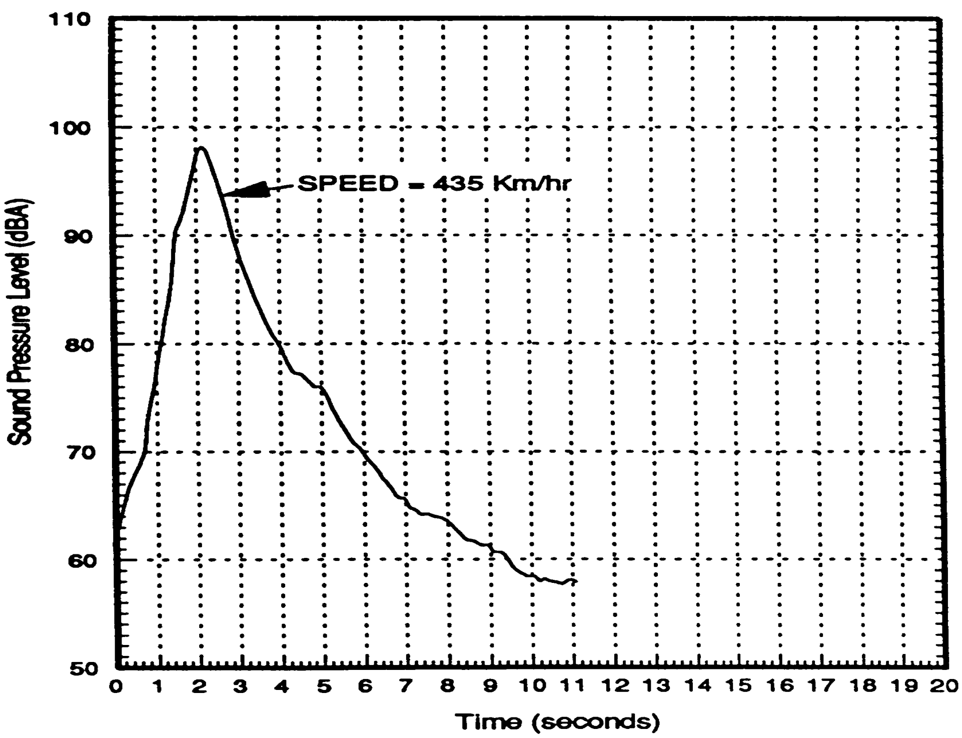

Figure A-6 Time History of A-weighted Sound Level of Maglev at 25 m

The onset rate is related to the rate of approach of a moving vehicle. More correctly, it is related to the rate at which the vector distance between the sound source and the receiver diminishes. Both speed and distance figure into the process. Measured onset rates from two high-speed rail systems are plotted in Figure 2-6.

A.4.2 Research on Startle Effects

When the onset of sound is very sudden, people tend to be **startled**, or surprised, especially when they are not expecting it. Researchers have proposed various adjustments to account for the increased annoyance of fast-rising sound events. The most recent study into the added annoyance from rapid onset rates has been conducted in three parts by the US Air Force in connection with low-altitude military test flights. [16] The initial literature review resulted in an interim metric whereby an “onset rate-adjusted SEL” was used in noise impact analyses where such operations were conducted. The interim adjustment was an addition to the SEL of the passby, starting with 0 dB for onset rates up to 15 dB/sec, ramping up to a maximum of 5 dB for onset rates of 30 dB/sec and higher. Laboratory tests using simulated sound and people hired for the occasion followed, resulting in a revised adjustment. Finally, psychoacoustic tests were conducted in a real home environment with hired test subjects and the currently recommended adjustment was

[16] E. Stusnick, K. Bradley. “The Effect of Onset Rate on Aircraft Noise Annoyance.” USAF Report AL/OE-TR-1993-0170, October 1992.

developed. Again, the adjustment is 0 dB up to an onset rate of 15 dB/sec, but the ramp extends to an addition of 11 dB at an onset rate of 150 dB/sec, with the relationship:

$$\text{Adjustment to SEL} = 11 \log(\text{onset rate}) - 12.9, \text{ in decibels}$$

where:

$15 \text{ dB/sec} < \text{onset rate} < 150 \text{ dB/sec}$.

A.4.3 Startle Effects Applied to High-Speed Rail Impact Assessment

The interim metric adopted by US Air Force after the first stage of its study was cited as the basis for the suggested adjustment for noise from high-speed maglev operations in a report prepared for the Federal Railroad Administration-sponsored National Maglev Initiative (NMI).[17] The recommended adjustment at that time was to add 5 dB to SEL whenever the onset rate from a maglev passby exceeded 15 dB/sec. Since data are available to show onset rates as a function of speed divided by distance, it was possible to develop a curve defining the relationship between speed and distance within which the onset rate exceeds 15 dB/sec for a maglev train. The proposed onset rate adjustment was recommended for assessment of noise impact from maglev trains.

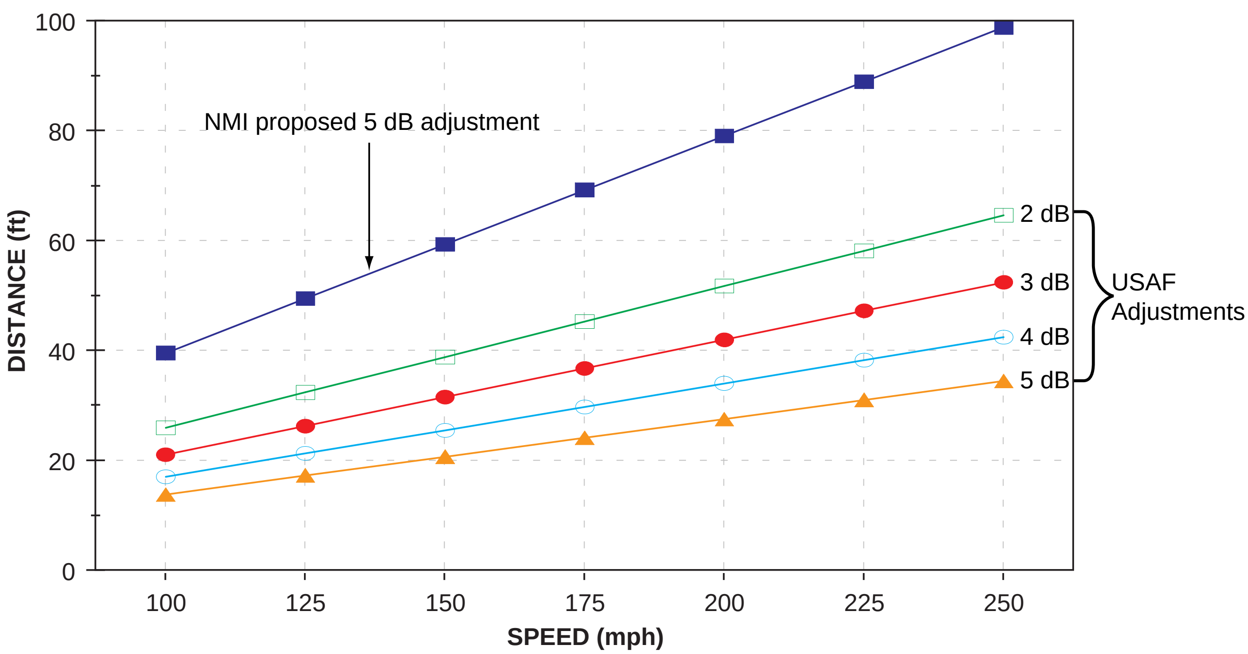

Figure A-7 Zones of Potential Startle Effect

[17] C. E. Hanson, P. Abbot, and I. Dyer. "Noise from High Speed Maglev Systems," US Department of Transportation, Federal Railroad Administration, Report No. DOT/FRA/NMI - 92-18, January 1993.

Applying the same approach, but using the latest revised US Air Force onset rate adjustments starting with 0 dB at 15 dB/sec, results in the relationships shown in Figure A-7. The new Air Force adjustments of 2 dB to 5 dB are plotted along with the original NMI proposed adjustment of 5 dB. The revised adjustments result in the potential for startle to be confined to a much narrower region than was obtained using the NMI method.

The following issues remain unresolved regarding application of the Air Force research to determine the startle effects of high speed rail:

1. What is the effect of scheduled events, such as train passbys, vs. "surprise" events, such as military training flights? Since high-speed trains always will be on the same track and on a schedule, it may be reasonable to expect habituation for long-term residents. Hence, an adjustment to every SEL from passing high-speed trains appears excessive.

2. Sound levels from train passbys are not as high, nor are onset rates as great as they are from low altitude military aircraft. Hence, the startle effect may not be the same.

3. The onset rate adjustments as proposed by the Air Force when applied to high-speed rail systems (Figure A-6) take place in a distance close enough to be affected already by noise. There may be no further reason to add to the impact assessment.

Without better definition of the application of results of noise from aircraft overflights to noise from high-speed rail passbys, it is appropriate to consider startle effects as "additional information" included in the impact assessment, rather than to include a penalty in the calculation of noise exposure itself. What remains to be determined is an onset rate that could be considered significant enough to cause startle on a regular basis. Lacking any other direction from research, the onset rate that would cause a 3 dB adjustment for the Air Force has been adopted for this manual. The resulting distance vs speed relationship is given in Figure 4-2.

A.5 EFFECTS ON LIVESTOCK AND WILDLIFE

A.5.1 Summary

A wide range of studies have been conducted concerning noise effects on animals. For humans, annoyance is considered to be the primary environmental noise effect; thresholds for annoyance in terms of sound exposure have been determined by surveys as described in Section A.3. However, for animals, the effects are not easily determined. Usually the studies require introduction of a specific noise event like an aircraft overflight and a subsequent observation of animal response. Observations of response to noise range from no reaction or mild responses such as slight changes in body position to extreme responses such as panic and attempts to escape. Long-term effects that might change behavior tend to be affected by factors other than short term noise exposure, such as weather, predation, disease and other disturbances to animal populations. Conclusions from research conducted to date provide only preliminary indications of the appropriate descriptor, rough estimates of threshold levels for observed animal disturbance, and habituation characteristics of only a few species. Long-term effects continue to be a matter of speculation. Moreover, most of the noise events used in prior studies are related to aircraft overflights. Consequently, any criteria adopted for effects on animals by high-speed rail noise must be considered interim until further specific research results are known. Following are discussions of descriptors and levels from the literature.[18,19,20,21]

A.5.2 Noise Descriptor

A noise descriptor for noise effects on wildlife has not been universally adopted, but recent research indicates the sound exposure level (SEL) is the most useful predictor of responses. Characteristic of the bulk of research to date has been lack of systematic documentation of the source noise event. Many studies report "sound levels" without specifying the frequency spectrum or duration. A notable exception is a study sponsored by U.S. Air Force that identifies SEL as the best descriptor for response of domestic turkey poults to low-altitude aircraft overflights (ref. 21). Another report questions whether an A-weighted sound level used in the SEL for aircraft overflights is appropriate for animals since their hearing differs from humans (ref. 20). However, since no weighting has been established for representing the hearing characteristics of wild animals, the A-weighted sound level continues to be used.

A.5.3 Thresholds for Disturbance

Most studies have focused on identifying a noise level associated with disturbance effects, even if the type of noise event varied considerably from study to study. In the well-documented study that recommended SEL as the preferred descriptor, a threshold of response for disturbance ("100 percent rate of crowding") of domestic turkeys was identified as SEL = 100 dB (ref. 21). Even if the descriptors are not the same, many studies report levels in the vicinity of 100 dB as associated with an observable effect, as shown in Table A-1. The information in this table is taken from an extensive survey on aircraft noise effects.[22] Until more definitive information on thresholds can be developed, an interim criterion of SEL = 100 dB will be used for disturbance by high-speed rail operations.

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[18]K.M. Manci, D.N. Gladwin, R. Villella, and M.G. Cavendish. "Effects of aircraft noise and sonic booms on domestic animals and wildlife: a literature synthesis." U.S. Fish and Wildlife Service National Ecology Research Center, Ft. Collins, CO., Report NERC-88/29, 1988.

[19]P. Dufour, "Effects of Noise on Wildlife and Other Animals: Review of Research Since 1971." US Environmental Protection Agency, Report 550/9-80100, July 1980.

[20]A. M. McKechnie, D.N. Gladwin. "Aircraft Overflight Effects on Wildlife Resources." US National Park Service, NPOA Report No. 93-8, November 1993.

[21]F. Bradley, C. Book, and A.E. Bowles. "Effects of Low-Altitude Aircraft Overflights on Domestic Turkey Poults," Report No. HSD-TR-90-034, US Air Force Systems Command, Noise and Sonic Boom Impact Technology Program, June 1990.

[22]K.M. Manci, D.N. Gladwin, R. Villella, and M.G. Cavendish. "Effects of aircraft noise and sonic booms on domestic animals and wildlife: a literature synthesis." U.S. Fish and Wildlife Service National Ecology Research Center, Ft. Collins, CO., Report NERC-88/29, 1988.

A.5.4 Habituation

There is evidence that some animals demonstrate reduced response to noise after prior exposure, but that a few species never become accustomed to, or **habituate**, to high noise levels. Researchers found that for turkeys, previous exposure to sound levels below the 100 dB threshold was sufficient to eliminate panic responses to higher level sounds (ref. 21). On the other hand, some animals and birds, such as the grizzly bear, Dall sheep, and least tern, have not been observed to habituate (ref. 20). Since habituation is found to be species-dependent, a general criterion cannot be developed at this time.

Table A-1 Summary of Noise Levels Associated with Effects on Animals and Birds (from ref. 20)

Animal Category	Species	Noise Level and Type (if known) Associated with Effect	Effect
Domestic Mammals	Dairy Cow	105 dB	Reduction in milk production
		97 dB	Changes in blood composition
		110 dB, 1 kHz	Changes in blood composition
	Swine	108-120 dB	Hormonal changes
		93 dB	Hormonal changes
		120-135 dB	Increased heart rate
	Sheep	100 dB “white noise”	Increased heart rate, respiration
		90 dB”white noise”	Decreased thyroid activity
		100 dB	Increase in number of lambs per ewe
Wild Mammals	Reindeer	Sonic booms	Startle
	Caribou	Aircraft	Startle, panic running
	Pronghorn antelope	77 dBA, helicopter	Running
Domestic Birds	Chicken	100 dB	Blood composition
		115 dB	Interrupt brooding
Wild Birds	Quail	80 dB	Accelerated hatching
	Canary	95-100 dB	Hearing loss
	Seabirds (general)	Sonic boom	Startle, flush from nest
	Tern	Sonic boom, frequent	Reduced reproduction
	California condor	Blasting, drilling, etc.	Flush from nest; abandon area
	Raptors	Sonic booms	Alarm

APPENDIX B
DETERMINING EXISTING NOISE[1]

This appendix provides additional detail for determining existing noise by: (1) full measurement, (2) computation from partial measurements, and (3) tabular look-up. The words "existing noise" and "ambient noise" are often used interchangeably.

The full set of options for determining existing noise at receivers of interest is as follows:

- OPTION 1: For non-residential land uses, measure a full hour's L_{eq} at the receiver of interest, during a typical hour of use on two non-successive days. The hour chosen should be the one in which maximum project activity will occur. The L_{eq} will be accurately represented.
- The three options for residential land uses are –
  1. OPTION 2: Measure a full day's L_{dn}. The L_{dn} will be accurately represented.
  2. OPTION 3: Measure the hourly L_{eq} for three typical hours: peak traffic, midday and late night. Then compute the L_{dn} from these three hourly L_{eq}'s. The computed L_{dn} will be slightly underestimated.
  3. OPTION 4: Measure the hourly L_{eq} for one hour of the day only, preferably during midday. Then compute the L_{dn} from this hourly L_{eq}. The computed L_{dn} will be moderately underestimated.

[1] This section has been adapted from Federal Transit Administration's noise guidance manual and is included here for completeness.

- OPTION 5: For all land uses, compute either the L_{eq} or the L_{dn} from a measured value at a nearby receiver – one where the ambient noise is dominated by the same noise source. The computed value will be represented with only moderate precision.
- OPTION 6: For all land uses, estimate either the L_{eq} or the L_{dn} from a table of typical values, depending upon distance from major roadways or upon population density. The resulting values will be underestimated significantly.

Option 1: For non-residential land uses, measure the hourly L_{eq} for the hour of interest

Full one-hour measurements are the most precise way to determine existing noise for non-residential receivers of interest. Such full-duration measurements are preferred over all other options. The following procedures apply to full-duration measurements:

- Measure a full hour's L_{eq} at the receiver of interest on at least two non-successive days during a typical hour of use. This would generally be between noon Monday and noon Friday, but weekend days may be appropriate for places of worship. On both days, the measured hour must be the same as that for which project noise is computed: the loudest facility hour that overlaps hours of noise-sensitive activity at the receiver.
- At all sites, locate the measurement microphone as shown in Figure 5-2 (Chapter 5), depending upon the relative orientation of project and ambient sources. A microphone location that is shielded somewhat from the ambient source is preferred. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 5).

Option 2: For residential land uses, measure the L_{dn} for a full 24 hours

Full 24-hour measurements are the most precise way to determine ambient noise for residential receivers of interest. Such full-duration measurements are preferred over all other options. The following procedures apply to full-duration measurements:

- Measure a full 24-hour's L_{dn} at the receiver of interest, for a single weekday (generally between noon Monday and noon Friday).
- At all sites, locate the measurement microphone as shown in Figure 5-2, depending upon the relative orientation of project and ambient sources. A microphone location that is shielded somewhat from the ambient source is preferred. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.

- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 5).

Option 3: For residential land uses, measure the hourly L_{eq} for three hours and then compute L_{dn}

An alternative way to determine L_{dn}, less precise than its full-duration measurement, is to measure hourly L_{eq}'s for three typical hours of the day and then to compute the L_{dn} from these three hourly L_{eq}'s. The following procedures apply to this partial-duration measurement option for L_{dn}:

- Measure the one-hour L_{eq} during each of the following time periods: once during peak-hour roadway traffic, once midday between the morning and afternoon roadway-traffic peak hours, and once between midnight and 5 am. For locations with no significant traffic patterns, it will be sufficient to measure a morning hour (7 am to 9 am), a midday hour (10 am to 4 pm), and a late night hour (10 pm to 7 am).

- Compute L_{dn} with the following equation:

$$L_{dn} \approx 10\log\left[(3)\cdot 10^{\frac{L_{eq}(peakhour)-2}{10}} + (12)\cdot 10^{\frac{L_{eq}(midday)-2}{10}} + (9)\cdot 10^{\frac{L_{eq}(latenight)+8}{10}}\right] - 13.8$$

This value of L_{dn} will be slightly underestimated, due to the subtraction of 2 decibels from each of the measured levels before their combination. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to its full-duration measurement.

- At all sites, locate the measurement microphone as shown in Figure 5-2, depending on the relative orientation of project and ambient sources. A microphone location that is shielded somewhat from the ambient source is preferred. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.

- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 5).

Option 4: For residential land uses, measure the hourly L_{eq} for one hour and then compute L_{dn}

The next level down in precision is to determine L_{dn} by measuring the hourly L_{eq} for one hour of the day and then to compute L_{dn} from this hourly L_{eq}. This method is useful when there are many sites in a General Assessment, or when checking whether a particular receiver of interest represents a cluster in a Detailed Analysis. The following procedures apply to this partial-duration measurement option for L_{dn}:

- Measure the one-hour L_{eq} during any hour of the day. The loudest hour during the daytime period is preferable. If this hour is not selected, then other hours may be used with less precision.

- Convert the measured hourly L_{eq} to L_{dn} with the applicable equation:

  For measurements between 7am and 7pm: $L_{dn} \approx L_{eq} - 2,$

  For measurements between 7pm and 10pm: $L_{dn} \approx L_{eq} + 3,$ and

  For measurements between 10pm and 7am: $L_{dn} \approx L_{eq} + 8.$

  The resulting value of L_{dn} will be moderately underestimated, due to the use of the adjustment constants in these equations. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to the more precise methods of determining L_{dn}.

- At all sites, locate the measurement microphone as shown in Figure 5-2, depending upon the relative orientation of project and existing sources. A microphone location that is shielded somewhat from the ambient source is preferred. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.

- Undertake all measurements in accordance with good engineering practice (see References 1 and 2 of Chapter 5).

Option 5: For all land uses, compute either L_{eq} or L_{dn} from a nearby measured value

A computation method comparable in precision to Option 4 is to determine the ambient noise, either L_{eq}(h) or L_{dn}, from a *measured* value at a nearby receiver – one where the ambient noise is dominated by the same noise source. This method is used to characterize noise in several neighborhoods by using a single representative receiver. Care must be taken to ensure that the measurement site has a similar noise environment to all areas represented. If measurements made by others are available, and the sites are equivalent, they can be used to reduce the amount of project noise monitoring. The following procedures apply to this computation of ambient noise at the receiver of interest:

- Choose another receiver of interest, called the "comparable receiver," at which:
  - The same source of ambient noise dominates.
  - The ambient $L_{CompRec}$ was **measured** with either OPTION 1 or OPTION 2 above.
  - The ambient measurement at the comparable receiver was made in direct view of the major source of ambient noise, unshielded from it by noise barriers, terrain, rows of buildings, or dense tree zones.

- From a plan or aerial photograph, determine: (1) the distance $D_{CompRec}$ from the comparable receiver to the near edge of the ambient source, and (2) the distance $D_{ThisRec}$ from this receiver of interest to the near edge of the ambient source.

- Also determine N, the number of rows of buildings that intervene between the receiver of interest and the ambient source.

- Compute the ambient noise at this receiver of interest with the applicable equation:

  If roadway sources dominate:

$$L_{\mathrm{This\,Rec}} \approx L_{\mathrm{Comp\,Rec}} - 15\log\left(\frac{D_{\mathrm{This\,Rec}}}{D_{\mathrm{Comp\,Rec}}}\right) - 3N$$

  If other sources dominate:

$$L_{\mathrm{This\,Rec}} \approx L_{\mathrm{Comp\,Rec}} - 25\log\left(\frac{D_{\mathrm{This\,Rec}}}{D_{\mathrm{Comp\,Rec}}}\right) - 3N$$

  The resulting value of $L_{ThisRec}$ will be moderately underestimated. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn}, compared to the more precise methods of determining ambient noise levels.

Option 6: For all land uses, estimate either L_{eq}(h) or L_{dn} from a table of typical values

The least precise way to determine the ambient noise is to estimate it from a table. A tabular look-up can be used to establish baseline conditions for a General Noise Assessment if a noise measurement cannot be made. It should not be used for a Detailed Noise Analysis. For this estimate of ambient noise:

- Read the ambient noise estimate from the relevant portion of Table 4-5. These tabulated estimates depend upon distance from major roadways, rail lines or upon population densities. In general, these tabulated values are significant underestimates. As explained previously, underestimates are intended to compensate for the reduced precision of the estimated ambients, compared to the options that incorporate some degree of measurements.

APPENDIX C
CONVERTING BETWEEN L_{max} AND SEL

This appendix provides procedures for:

1) computing L_{max} for a single high-speed train passby using the source reference levels in SEL and methods given in Chapters 4 and 5, and

2) estimating source reference levels in SEL for a General Assessment from either measured or specified values of the single-passby L_{max}.

The first SEL to L_{max} conversion may be useful in determining whether a proposed project or type of equipment will meet the noise limit defined in the project specifications, almost always given in terms of L_{max}. The second procedure, converting from L_{max} to SEL, involves computing reference SELs specific to a certain trainset or project noise specification, which may be different from the generalized levels given in this manual. A General Noise Assessment can then be performed based on measurements, equipment specifications, or project noise limits.

C.1 COMPUTING L_{max} FOR A SINGLE TRAIN PASSBY

The L_{max} conversion procedure from the reference SELs given in Chapter 4 (Initial Noise Evaluation) or Chapter 5 (Detailed Noise Analysis) to a single L_{max} value is summarized as follows:

Step 1. **Select Source Reference SEL(s)**. Classify the project into one of the vehicle categories defined in Table 4-2 or Table 5-2. For General Assessment, the speed regime (I, II or III) also must be selected from Table 4-2, which identifies the single dominant noise source for the given speed and the corresponding reference SEL. For Detailed Analysis, separate subsource SELs are listed in Table 5-2.

Step 2. **Adjust for Project Operating Conditions**. Adjust the reference SEL (General Assessment) or each applicable subsource reference SEL (Detailed Analysis) at 50 feet for operating conditions for the project or for a particular corridor segment, using the methods in Section 4.2.1 or 5.2.2.

Step 3. **Adjust for Propagation with Distance**. Propagate each adjusted SEL out to the specified distance (if other than the reference distance of 50 feet), accounting for attenuation with distance, shielding, and ground effect, if necessary, using the methods in Section 4.2.2 or 5.2.3.

Step 4. **Convert SEL to L_{max}**. Compute L_{max} using the equations in Table C-1. For the Detailed Analysis method, choose the largest of the subsource L_{max} values as the overall L_{max} for the train passby.

Table C-1 Computation of L_{max} for a High-Speed Train Passby using General Assessment or Detailed Analysis Method

Applicable Parameters		SEL–to–L_{max} Equation
General Assessment	**Detailed Analysis**	
Speed Regime I	Propulsion Subsource	
use *len* = **total** length of power units, in feet	use *len* = length of **one** power unit, in feet	$L_{\max} = SEL - 10\log\left(\frac{len}{S}\right) + 10\log(2\alpha) - 3.3$
Speed Regime II	Wheel/Rail or Guideway/Structural Subsource	$L_{\max} = SEL - 10\log\left(\frac{len}{S}\right) + 10\log[2\alpha + \sin(2\alpha)] - 3.3$
use *len* = **total** length of train, in feet	use *len* = length of coaches only, in feet	
Speed Regime III	Aerodynamic Subsources	
use *len* = **total** length of train, in feet	use *len* = subsource length as defined in Table 5-2, in feet	$L_{\max} = SEL - 10\log\left(\frac{len}{S}\right) + 10\log(2\alpha) - 3.3$

Variables are defined as follows:

$$S = \text{train speed, in mph,}$$

$$\alpha = \tan^{-1}\left(\frac{len}{2d}\right), \text{ in radians,}$$

$$len = \text{length as defined above, and}$$

$$d = \text{receiver distance from track centerline, in feet.}$$

C.2 COMPUTING REFERENCE SEL'S FROM L_{MAX} FOR GENERAL ASSESSMENT METHOD

If L_{max} for a specific trainset is available from vehicle noise measurements, manufacturer specifications, or a specific project limit, it is possible to estimate the equivalent reference SELs to use in the General Noise Assessment (Chapter 4) procedure presented in this manual. The Detailed Noise Analysis (Chapter 5) method, however, involves the use of detailed component, or subsource, SELs that cannot be determined accurately from a single passby L_{max} value. Determination of subsource SELs requires more complex measurement techniques, such as a microphone array or controlled single microphone measurements with a low sound barrier to shield wheel/rail noise, in order to isolate certain source components.

If a specific L_{max} value is available for the proposed trainset and Detailed Noise Analysis procedures are to be followed, it is recommended that the subsource SELs provided in Chapter 5 be used to first calculate L_{max} as described in Appendix C (Section C.1). This calculated L_{max} can then be compared with the specified or measured L_{max} and if necessary, one or more of the subsource SELs can be adjusted to account for the discrepancy. This may be an iterative process until the computed L_{max} and the specified L_{max} are the same. This technique should be exercised with caution, however, since judgement and understanding of the subsource mechanisms are required to determine which of the subsource SELs should be adjusted.

The procedure for converting L_{max} to a reference SEL for use in the General Noise Assessment method is summarized as follows:

Step 1. **Identify Vehicle Category**. Classify the project into one of the vehicle type categories listed in Table 4-2.

Step 2. **Identify Major Sound Source and Parameters**. Identify the appropriate speed regime I, II or III from Table 4-2. The speed regime establishes the dominant sound source for the given speed (propulsion, wheel/rail or aerodynamic). For the vehicle category, obtain noise model parameters such as speed coefficient, reference length, and reference speed corresponding to the speed regime from Table 4-2.

Step 3. **Convert L_{max} to SEL**. Compute SEL using the equations in Table C-2. This computation yields the SEL for the operating conditions and distance corresponding to the L_{max} measurement or specification.

Step 4. **Normalize to Reference Conditions**. Adjust the resulting SEL to the reference distance and operating conditions of Table 4-2, using the equation in Table C-2. This adjustment yields a new reference SEL appropriate for comparison with the values listed in Table 4-2.

Table C-2 Computation of SEL for a High-Speed Train Passby from L_{max} for General Assessment	
To convert from L_{max} to SEL:	
Speed Regime I	$SEL = L_{\max} + 10\log\left(\frac{len}{S}\right) - 10\log(2\alpha) + 3.3$ where *len* = total length of power unit(s), in feet
Speed Regime II	$SEL = L_{\max} + 10\log\left(\frac{len}{S}\right) - 10\log[2\alpha + \sin(2\alpha)] + 3.3$ where *len* = total length of train, in feet
Speed Regime III	$SEL = L_{\max} + 10\log\left(\frac{len}{S}\right) - 10\log(2\alpha) + 3.3$ where *len* = total length of train, in feet
To normalize back to Reference Conditions of Table 4-2:	
$SEL_{ref} = SEL + K\log\left(\frac{S_{ref}}{S}\right) + 10\log\left(\frac{len_{ref}}{len}\right) - 15\log\left(\frac{50}{d}\right)$	
$SEL_{ref} = SEL$ adjusted to reference parameters of Table 4-2 at reference distance, $K =$ Speed coefficient (from Table 4-2), $S_{ref} =$ Reference speed, mph (from Table 4-2), $S =$ Train speed, mph, $len_{ref} =$ Reference length, feet (from Table 4-2), $d =$ receiver distance from track centerline, feet, and $\alpha = \tan^{-1}\left(\frac{len}{2d}\right)$, radians.	

APPENDIX D
GLOSSARY OF TERMS

A-weighting – A method used to alter the sensitivity of a sound level meter with respect to frequency so that the instrument is less sensitive at frequencies where the human ear is less sensitive. Also written as dBA.

Aeroacoustic – Acoustical waves generated by pressure fluctuations in moving air.

Ambient – The pre-project background noise or vibration level.

Alignment – The horizontal location of a railroad as described by curved and tangent track.

Auxiliaries – The term applied to a number of separately driven machines, operated by power from the main engine. They include the air compressor, radiator fan, traction motor blower, exciter for the main generator and the boiler blower.

Ballast Mat – A 2- to 3-inch-thick elastomer mat placed under the normal track ballast on top of a rigid slab.

Ballast – Selected material placed on the roadbed for the purpose of holding the track in line and at surface.

Cab – The space in the power unit containing the operating controls and providing shelter and seats for the engine crew.

Catenary – On electric railroads, the term describing the overhead conductor that is contacted by the pantograph or trolley, and its support structure.

Coach – A passenger-carrying rail car, usually with a center aisle and two rows of seats.

Consist – The total number and type of cars and locomotives in a trainset.

Continuous Welded Rail – A number of rails welded together in lengths of 400 feet or longer.

Corrugated Rail – A rough condition on the rail head of alternate ridges and grooves, which develops in service.

Cross Tie – The transverse member of the track structure to which the rails are spiked or otherwise fastened to provide proper gage and to cushion, distribute, and transmit the stresses of traffic through the ballast to the roadbed.

Crossover – Two turnouts with the track between the frogs arranged to form a continuous passage between two nearby and generally parallel tracks.

Cut – A term used to describe a railbed at a lower level than the surrounding ground.

dB – *see Decibel*

dBA – *see A-weighting*

Decibel – A unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the logarithm of this ratio. Also written as dB.

Descriptor – A quantitative metric used to identify a specific measure of sound level.

DNL – *see* L_{dn}

DOT – The Department of Transportation. An agency of the U. S. government having jurisdiction over matters pertaining to all modes of transportation.

Electrification – A term used to describe the installation of overhead wire or third rail power distribution facilities to enable operation of trains hauled by electric locomotives.

Embankment – A bank of earth, rock or other material constructed above the natural ground surface.

Equivalent Level – The level of a steady sound which, in a stated time period and at a stated location, has the same A-weighted sound energy as the time-varying sound. Also written as L_{eq}.

Flange – The vertical projection along the inner rim of a wheel that serves, together with the corresponding projection of the mating wheel of a wheel set, to keep the wheel set on the track.

Flow Separation – Loss of adherence of air to parts of the train's outer surface.

FRA – The Federal Railroad Administration. An agency of the U. S. Department of Transportation with jurisdiction over matters of railroad safety and research.

Frequency – Of a phenomenon that occurs periodically in time, the number of times that the quantity repeats itself in 1 second.

Frog – A track structure used at the intersection of two running rails to provide support for wheels and passageways for their flanges, thus permitting wheels on either rail to cross the other.

Gage (of track) – The distance between the gage lines, measured at right angles thereto.

Gage Line – A line 5/8-inch below the top of the center line of head of running rail or corresponding location of tread portion of other track structures along that side which is nearer the center of the tracks.

Gas-Turbine Electric Locomotive – A power unit in which a gas turbine drives electric generators supplying current to electric traction motors on the axles.

Grade Crossing – The point where a rail line and a motor vehicle road intersect.

Guideway – Supporting structure to form a track for rolling- or magnetically-levitated vehicles.

Head-End Power – A system of furnishing electric power for a complete railway train from a single generating plant in the power unit.

Hourly Average Sound Level – The time-averaged A-weighted sound level, over a 1-hour period, usually calculated between integral hours. Also known as L_{1h}.

Idle – The speed at which an engine runs when it is not under load.

Intermodal Car – A rail car designed specifically for handling piggyback trailers or containers, or both.

Intermodal Traffic – Freight moving via at least two different modes of transport, e.g., truck-to-rail.

Jointed Rail – A system of joining rails with steel members designed to unite the abutting ends of contiguous rails.

L_{1h} – *see Hourly Average Sound Level*

L_{AE} – Power-averaged value of sound exposure within 10 dB of L_{Amax}, sampled at a time interval of 5/3 second. Used in Japan.

$L_{Aeq,P}$ – Equivalent A-weighted sound-level, energy averaged over the time of passby (train length). Used in Europe.

$L_{Aeq,1h}$ – Sound-pressure level, energy averaged over one hour. See also Hourly Average Sound Level. Used in Europe.

L_{Amax} – Power-averaged "slow" maximum level ($L_{max,s}$) of 20 consecutive train passbys. Used in Japan.

L_{dn} – The sound exposure level for a 24-hour day calculated by adding the sound exposure level obtained during the daytime (7 a.m. to 10 p.m.) to 10 times the sound exposure level obtained during the nighttime (10 p.m. to 7 a.m.). This unit is used throughout the U.S. for environmental impact assessment. Also written as DNL.

L_{eq} – *see Equivalent Level*

L_{max}(mean) – *see $L_{Aeq,P}$* (used in Scandinavia)

$L_{p,1h}$ – *see $L_{Aeq,1h}$*

$L_{p,p}$ – *see $L_{aeq,P}$*

Locomotive – A self-propelled, non-revenue rail vehicle designed to convert electrical or mechanical energy into tractive effort to haul railway cars. (*see also Power Unit*)

Lead Unit – The first and controlling power unit in a series of locomotives pulling the same train.

Main Line – The principal line or lines of a railway.

Maglev – Magnetically-levitated vehicle; a vehicle or train of vehicles with guidance and propulsion provided by magnetic forces. Support can be provided by either a electrodynamic system (EDS) wherein a moving vehicle is lifted by magnetic forces induced in the guideway, or a electromagnetic system (EMS) wherein the magnetic lifting forces are actively energized in the guideway.

Maximum Sound Level – The highest exponential-time-average sound level, in decibels, that occurs during a stated time period. Also written as L_{max}. The standardized time periods are 1 second for $L_{max,\ slow}$ and 0.125 second for $L_{max,\ fast}$.

Multiple Unit (MU) – A term referring to the practice of coupling two or more power units or electric passenger cars together with provision for controlling the traction motors on all units from a single controller.

Noise – Any disagreeable or undesired sound or other audible disturbance.

Octave – The frequency interval between two sounds whose frequency ratio is 2.

Pantograph – A device for collecting current from an overhead conductor (catenary), consisting of a jointed frame operated by springs or compressed air and having a current collector at the top.

Peak Particle Velocity (PPV) – The peak signal value of an oscillating vibration velocity waveform. Usually expressed in inches/second.

Peak-to-Peak (P-P) Value – Of an oscillating quantity, the algebraic difference between the extreme values of the quantity.

Power Unit – A self-propelled vehicle, running on rails and having one or more electric motors that drive the wheels and thereby propel the locomotive and train. The motors obtain electrical energy either from a rail laid near to, but insulated from, the track rails, or from a wire suspended above the track. Contact with the wire is made by a pantograph mounted on top of the unit.

Radius of Curvature – A measure of the severity of a curve in a track structure based on the length of the radius of a circle that would be formed if the curve were continued.

Rail – A rolled steel shape, commonly a T-section, designed to be laid end to end in two parallel lines on cross ties or other suitable supports to form a track for railway rolling stock.

Receiver/Receptor – A stationary far-field position at which noise or vibration levels are specified.

Retarder – A braking device, usually power-operated, built into a railway track to reduce the speed of cars by means of brake shoes which, when set in position, press against the sides of the lower portions of the wheels.

Right-of-Way – Lands or rights used or held for railroad operation.

Root Mean Square (RMS) – The average or "mean" level of an oscillating waveform. Obtained by squaring the value of amplitudes at each instant of time. The squared values are then added and averaged over the sample time.

SEL – *see Sound Exposure Level*

Siding – A track auxiliary to the main track for meeting or passing trains.

Sound Exposure Level – The level of sound accumulated over a given time interval or event. Technically, the sound exposure level is the level of the time-integrated mean square A-weighted sound for a stated time interval or event, with a reference time of one second. Also written as SEL.

Sound – A physical disturbance in a medium that is capable of being detected by the human ear.

Sub-Ballast – Any material of a superior character, which is spread on the finished subgrade of the roadbed and below the top-ballast, to provide better drainage, prevent upheaval by frost, and better distribute the load over the roadbed.

Subgrade – The finished surface of the roadbed below the ballast and track.

Switch – A track structure used to divert rolling stock from one track to another.

Tangent Track – Track without curvature.

Terminal – An assemblage of facilities provided by a railway at a terminus or at an intermediate point for the handling of passengers or freight and the receiving, classifying, assembling and dispatching of trains.

Top-Ballast – Any material of a superior character spread over a sub-ballast to support the track structure, distribute the load to the sub-ballast, and provide a good initial drainage.

Turbulent Boundary Layer – Fluctuations in the air adjacent to the body of a vehicle moving at high speed.

Track Crossing – A structure, used where one track crosses another at grade, and consisting of four connected frogs.

Track – An assembly of rail, ties and fastenings over which cars, locomotives, and trains are moved.

Traction Motor – A specially designed direct current series-wound motor mounted on the trucks of locomotives and self-propelled car to drive the axles.

Trainset – A group of coupled cars including at least one power unit.

Truck – The complete assembly of parts including wheels, axles, bearings, side frames, bolster, brake rigging, springs and all associated connecting components, the function of which is to provide support, mobility and guidance to a railroad car or locomotive.

Turnout – An arrangement of a switch and a frog with closure rails, by means of which rolling stock may be diverted from one track to another.

VdB – *see Vibration Velocity Level*

Vibration Velocity Level – 10 times the common logarithm of the ratio of the square of the amplitude of the vibration velocity to the square of the amplitude of the reference velocity. Also written as VdB.

Vibration – An oscillation wherein the quantity is a parameter that defines the motion of a mechanical system.

Vortex Shedding – A flow separation (*see definition above*) wherein the air departs periodically in a spinning motion.

Wheel Flat – A localized flat area on a steel wheel of a rail vehicle, usually caused by skidding on steel rails, causing a discontinuity in the wheel radius.

Wheel Squeal – The noise produced by wheel-rail interaction, particularly on a curve where the radius of curvature is smaller than allowed by the separation of the axles in a wheel set.

Wye – A triangular arrangement of tracks on which locomotives, cars and trains may be turned.

Yard – A system of tracks within defined limits provided for making up trains, storing cars, and other purposes, over which movements not authorized by time table or by train-order may be made, subject to prescribed signals and rules, or special instructions.